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BEAMING ELECTRICITY VIA RELAY SATELLITES IN SUPPORT OF DEPLOYED COMBAT FORCES

by

Thomas R. Essenpreis

September 2012

Thesis Advisor: Mark Rhoades
Second Reader: Daniel Bursch

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The logistics required to supply military forces based in remote hostile territory can be onerous. A major component of those supplies is the fuel required to operate generators that provide electrical power. This research sought to determine the feasibility for a space-based system using wireless power transfer technology to relay power to a remote base from a location with a commercial grid. The two wireless power transfer methods examined in this research both use electro-magnetic radiation. One method operates in the part of the spectrum known as radio using high power transmitters and the other operates in the near infrared using lasers. These two methods were integrated into architectures and modeled and analyzed to determine which one was the more feasible. The result is that while both methods are possible the radio wireless power transfer method loses far more power from end to end than does the laser method and also needs to be in a far lower orbit in order to operate at all, requiring more spacecraft for global coverage. The laser based relay does have many challenges however including weather effects and safety concerns.

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BEAMING ELECTRICITY VIA RELAY SATELLITES IN SUPPORT OF DEPLOYED COMBAT FORCES

Thomas R. Essenpreis
Captain, United States Air Force
B.S. Mechanical Engineering, Southern Illinois University Edwardsville, 2003

Submitted in partial fulfillment of the
requirements for the degree of

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NAVAL POSTGRADUATE SCHOOL
September 2012

Author: Thomas Essenpreis

Approved by: Mark M. Rhoades
Thesis Advisor

Daniel W. Bursch
Second Reader

Rudolph Panholzer,
Chair, Space Systems Academic Group

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ABSTRACT

The logistics required to supply military forces based in remote hostile territory can be onerous. A major component of those supplies is the fuel required to operate generators that provide electrical power. This research sought to determine the feasibility for a space-based system using wireless power transfer technology to relay power to a remote base from a location with a commercial grid. The two wireless power transfer methods examined in this research both use electro-magnetic radiation. One method operates in the part of the spectrum known as radio using high power transmitters and the other operates in the near infrared using lasers. These two methods were integrated into architectures and modeled and analyzed to determine which one was the more feasible. The result is that while both methods are possible the radio wireless power transfer method loses far more power from end to end than does the laser method and also needs to be in a far lower orbit in order to operate at all, requiring more spacecraft for global coverage. The laser based relay does have many challenges however including weather effects and safety concerns.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

cm	Centimeter
COL	Contingency Operating Location
dc	Direct Current
EHF	Extremely High Frequency
GEO	Geosynchronous Orbit
GHz	Gigahertz
laser	Light Amplification by Stimulated Emission of Radiation
MEP	Mobile Electric Power
kHz	Kilohertz
km	Kilometer
kW	Kilowatt
kW/h	Kilowatt/hour
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MW	Megawatt
RF	Radio Frequency
STK	Satellite Toolkit
U.S.	United States
VMJ	Vertical Muli-Junction
W	Watts

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I. INTRODUCTION

A. CONTEXT

The past decade, the U.S. has found its military deployed around the world. This is nothing new to U.S. forces that have, since the end of the Second World War, been continuously deployed or stationed outside of the continental U.S. In the last decade's conflicts, the U.S. has fought, and become an occupying force. These conflicts have occurred in areas that have little infrastructure and where guerrilla forces operate to impede that occupation.

1. Logistics

An often-quoted idiom says *"an army marches on its stomach."* (The Free Dictionary, 2012) Since the modern military rarely marches on foot to battle the adage might as well be modified to say that an army rolls on its fuel tanks. Fossil fuels, because of their energy density and ease of transport are the power source of choice of a modern military. They are used to power air and ground vehicles but they are also used to provide electricity for numerous forward bases. Those bases all have generators that run 24 hours a day to keep communications, lights, and air conditioners operating along with the many other pieces of support equipment from computers to toasters that are part of day to day life at a modern forward base. In the current conflict, in Afghanistan, that the U.S. is engaged in on an average week Bagram Airfield consumes nearly 1.9 million gallons of fuel (McDougal, 2012). This energy demand forces the establishment of logistics to support it. These supply lines stretch thousands of miles over sea, land and sometimes even air to provide forward locations the fuel they need to operate. Fuel is transported from the refinery and port in Karachi, Pakistan and is driven overland into Afghanistan in 10,000-gallon trucks operated by local nationals (Blanchfield, 2005). The fully burdened cost of ground delivered fuel has been estimated at $400 per gallon for fuel delivered by ground to $1000 per gallon for fuel that is delivered by air (Tiron, 2009).

2. Vulnerability of Logistics

In the remote areas this supply link can be extremely difficult to execute. In June 2008 alone, 44 trucks carrying 220,000 gallons were lost to insurgent attacks (Tiron, 2009). Most fuel is brought in by tanker truck at slow speed through many miles of bad roads, Afghanistan has 21,000 km of roads of which 18,207 are unpaved, in territory peppered with insurgents to whom a fuel truck is a tempting target (Blanchfield, 2005). In order to ensure this valuable commodity reaches its destination in the Helmand province of Afghanistan civilian fuel convoys are escorted by companies of Marines whose mission is *"to provide armed escort for the local nationals."* (Jackson, 2012) The cost is not merely in dollars as some 80% of U.S. military casualties in Afghanistan were due to improvised explosive devices, which are often placed in the path of supply convoys (Tiron, 2009). This statistic frames the environment where some U.S. bases were found so remote and the territory surrounding them so hostile that fuel had to be flown in and air dropped only making the delivery cost more extreme. Since the bulk of these convoys are carrying fuel it would be a valuable exercise to explore alternative energy delivery options that do not require extensive exposure of the transport method to guerrillas with improvised explosive devices.

B. PURPOSE AND RESEARCH QUESTION

The purpose of this research is to postulate, analyze and compare a pair of space based, electricity relay alternatives to the costly ground transport method U.S. forces rely on today. Based on this research U.S. forces could develop systems to more efficiently operate far from their base of supply. The question this research will strive to answer: Could a space based electricity beaming relay be a solution to the costly logistics of transporting large quantities of fuel to remote bases?

C. SCOPE LIMITATIONS AND METHODOLOGY

The scope of this research has two parts. First it examines the existing literature on the latest technologies available for wireless electricity transfer and provides a summary of that research. Based on those technologies, two architectures are postulated and analyzed for the performance to provide electrical power via space-based relay. The

methodology for this research includes a literature review of the technologies associated with electricity beaming as well as the guidance associated with expeditionary military electrical design. The knowledge gained from that literature review is then applied to the critical element design of potential architectures for space power relay. Following the design is an analysis of those architectures conducted using the Satellite Tool Kit (STK) software suite.

D. CHAPTER SUMMARY

1. Chapter II - Background

This chapter contains background information to orient the reader with several concepts that will be used later in the design and analysis chapters. These topics include orbital motion, electricity beaming technologies, global commercial electricity availability, expeditionary electrical infrastructure as well as an overview of expeditionary military basing. This will provide the theoretical detail and contextual environment in which to postulate an architecture.

2. Chapter III – System Architectures

In order to model and analyze a space based electricity relay in Chapter IV, it will be necessary to define certain elements of the technical solution. Using the technical and environmental constraints established in Chapter II, this chapter will construct several potential architectures to complete a space based electricity relay.

3. Chapter IV – Presentation and Analysis of Data

The architectures defined in Chapter III are modeled using STK. The results of those models are presented. A description of how each model took shape was developed is provided followed by graphical depictions. STK generated reports are presented illustrating how the relay functions over time. Lastly, an analysis of the results for each model is given.

4. Chapter V – Conclusions and Recommendations

The final chapter begins with a general description of the research and analysis conducted. At this point the original research question is addressed and conclusions are drawn based on the results presented in Chapter IV. Finally areas for future work that could enhance this area of research are suggested.

II. BACKGROUND

The use of a ground-based system to transmit energy above the Earth's atmosphere to a relay spacecraft in orbit and then back down to one or many ground receiving sites requires a detailed explanation of the technologies and physical limitations that influence the design. How the system transmits that energy and the relative motion of the vehicle relaying it are critical design factors. Additionally the selection criteria for an electricity uplink location as well as a discussion of the interfaces at the electricity receiving site and the requirements of the spacecraft payload are worthy of discussion. This chapter will provide a detailed explanation and provide the context of the architecture defined later in this research paper.

A. ORBITAL MOTION

1. The Fundamentals

Our modern understanding of the motion of the celestial bodies has its roots in the efforts of the Greeks to catalog and describe their observations of lunar phases and eclipse cycles. Our understanding was not taken further until the late 1600s. Using the predictions of Nicolaus Copernicus and the meticulous observations of Tycho Brahe as his basis Johannes Kepler was able to concisely describe the elliptical motion of the planets (which would also apply to Earth orbiting spacecraft) in his three laws. The first law is that the orbit of each planet is an ellipse with the Sun at one focus. The second is that a line joining the planet to the Sun sweeps out equal areas in equal times. The third and final Keplerian law is that the square of the period of a planet is proportional to the cube of its mean distance from the Sun (Larson & Wertz, 2005).

While Kepler did succeed in describing celestial mechanics it was Newton that synthesized Kepler's work with terrestrial dynamics work of Galileo Galilei into the three laws of mechanics. The fact is though that the first law (the law of inertia) is a special case of the second law and the third law (law of action and reaction) simply follows from

the second. Newton's true innovation to dynamics is his second law known as the fundamental law of dynamics, which is that force is equal to the product of the inertial mass and the acceleration (Capderou, 2005).

Using Newton's laws the study of celestial mechanics defined the motion of the bodies of the solar system. The branch of that study known as astrodynamics deals with the description of the orbits of artificial spacecraft. An orbit is a trajectory that describes an ellipse that is periodic in nature relative to the Earth (Montenbruck & Gill, 2000).

2. Orbit types

Describing the fundamental nature of orbits does not in and of itself highlight the usefulness of an orbit. The usefulness of an orbit is a function of its attributes relative to the application. Due to the commercial and technical limitations of existing launch vehicles as well as the limited set of requirements of existing space applications a common set of attributes described by a specific name has developed. The first of these is Low Earth Orbit (LEO), which describes a nearly circular orbit in the altitude range of 300 to 1500 km. Spacecraft in LEO can have a variety of inclinations, which affects where over the Earth the spacecraft passes on a regular basis. The inclination is selected depending on the application. Inclination is the angle between the orbital plane and the equator. Common applications that use LEO are space observatories, remote sensing and manned spaceflight. The second common orbit is Medium Earth Orbit (MEO). MEO describes a nearly circular orbit in the altitude range of anywhere above LEO but below Geosynchronous. This orbit has been used previously by systems broadcasting precision navigation and timing signals and has the advantage of providing the spacecraft with a large area of coverage on the Earth as well as the ability to dwell above any particular ground station's horizon for a significant time while also not competing for space in the crowded higher orbit. The final orbit that will be discussed here is the Geosynchronous Orbit (GEO), which describes a nearly circular orbit at an altitude of 35,800 km. The primary applications undertaken at GEO are the communication spacecraft that benefit from having a constant view of one area of the surface of the Earth and a large coverage area (Montenbruck & Gill, 2000).

B. ELECTRICITY BEAMING TECHNOLOGIES

1. Introduction

The technologies available today to transmit electricity through free space have roots with the work of Heinrich Hertz. His work centered on radio wave propagation for communications purposes, but demonstrated the concept of transmitting and receiving high frequency electricity without the use of wires as well as the technique of focusing of radio waves through the modification of antenna shape. The first real attempt to transmit electricity without wires was undertaken by Nikola Tesla in 1899. His efforts were focused on the use of voltages near 100 million volts and frequencies in the 150 kHz range. None of this early work produced successful results. The primary reason for the lack of further development at that time was due to the realization that very short wavelengths and/or optical reflectors or lenses would be required. Equipment to provide even a small amount of transmitted electricity at very short wavelengths would not be available for 50 years (Brown, 1984). The use of light produced by lasers to transmit and specialized photovoltaic cells to receive electricity is being researched at the present time and developments have shown success (Nayfeh, Fast, Raible, Dinca, Tollis, & Jalics, 2011).

2. Radio Frequency (RF) Wireless Electricity

The Department of Energy and the National Aeronautics and Space Administration revived experiments designed to develop the use of the Extremely (EHF) radio portion of the electromagnetic spectrum for electricity transmission in the mid-1970s with some success. These experiments developed the basic concept of operations for all future microwave RF electricity transmission. The concept involved using a parabolic transmitting antenna focused at a distant receiving array. That distant array was made up of numerous half-wave dipole antennas, which terminated into rectifiers. These devices came to be known as rectennas (Brown, 1984). The dipole size and therefore the size of the overall rectenna is proportional to the operating frequency by

$$(1.1) \quad \lambda = \frac{c}{f}$$

where λ is wavelength, f is frequency and c is the speed of light (Gordon & Morgan, 1993). These expermiments at operating frequencies centering on 2.5 Ghz (12 cm wavelength) achieved an overall direct current (dc) to dc efficiency of 54 % and were able to transmit 30 kW the distance of 1609 meters using a 26.8 square meter rectenna array (Brown, 1984). One of the challenges with transmitting RF energy through the atmosphere is that of path loss due to atmospheric effects. Figure 1 shows the how the atmospheric attenuation varies over wavelength per km.

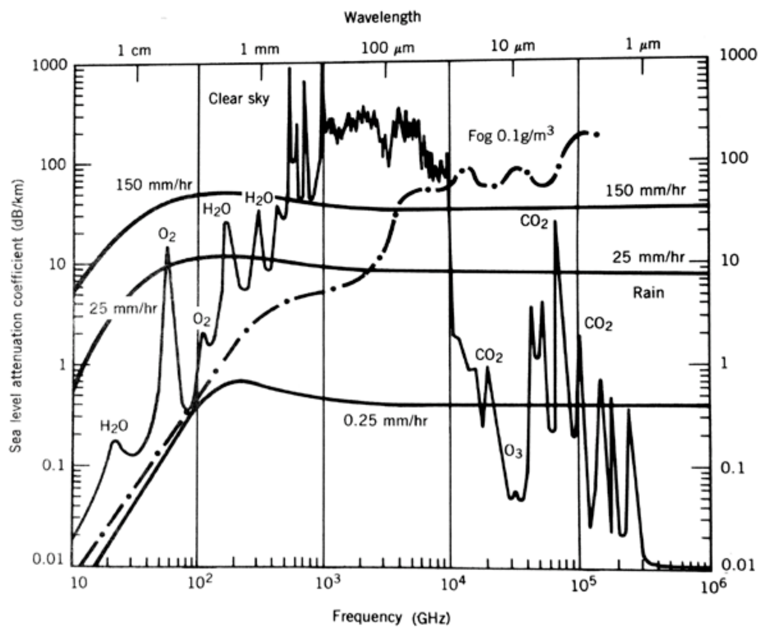

Figure 1. Atmospheric Path Loss (From Gordon & Morgan, 1993)

Work to refine compact wireless transfer of electricity through RF focuses on increasing the dc to dc efficiency, reducing the physical size of the rectenna and integration of that rectenna into a monolithic substrate. Given the proportionality of rectenna size to frequency discussed above it is clear why research has trended towards the use of much higher frequencies and smaller wavelengths. Using a two dimensional slot antenna placed on a silicon substrate through the use of traditional photolithography and optimized for 94 Ghz experiments have shown a 93% RF to dc collection efficiency and a 72% conversion efficiency. This slot antenna has been shown to be capable of converting power at densitites as high as 1 Watt/cm^2 (Mojarradi, et al., 2008).

Increasing the size of a space based antennas is another area of work. Deployable mesh antenna's with aperature sizes on the order of 12.5 meters have been flown (Thomson, 2002).

Another area of research and the fundamental driver for receiving and transmitting antenna sizing is the RF beam divergence over distance through diffraction. There will be a main lobe of the beam which will contain 84% of the transmitted power. This divergence is a function of the distance from transmitter to reciever, the wavelength of the RF energy and the relative sizes of the receiving rectenna and transmitting antennas. This is described by equation (1.2) where D_t is the diameter of the transmitting antenna, D_r is the diameter of the receiving rectenna, λ is wavelength like above and x is the distance from transmitter to receiver. Notice that this equation is independent of the amount of power in the beam.

$$(1.2) \quad \frac{D_t D_r}{\lambda x} = 2.44$$

The power intensity within that main lobe at the receiving rectenna is given by equation (1.3). Where I_0 is power density and P_t is the transmitted power (Potter, et al., 2009).

$$(1.3) \quad I_0 = \frac{\pi P_t}{4}\left(\frac{D_t}{\lambda x}\right)^2$$

Using these principles and constraints a system designed using RF to beam power can be sized and optimized.

3. Laser Fundamentals

Beginning with Max Planck's discovery, for which he won the Nobel Prize in 1918, that light is just another form of electromagnetic radiation the stage was set for the invention of the laser (Ekstrand, 1920). The word laser is in fact a very descriptive acronym that stands for Light Amplification by Stimulated Emission of Radiation. A laser is simply a light source that happens to possess the ability to direct the light it emits

into a single direction and usually at a specific wavelength. The laser itself was invented by Theodore Maiman in 1960 and today lasers have countless uses and new uses are being developed (Laserfest.org, 2012).

There are three factors that are important to consider about lasers in the context of transmitting large amounts of energy. These factors are first the amount of power that a laser, which could be integrated into the architecture postulated in this research, could be expected to produce. This factor can vary widely from a few kW to many MW depending on the technology selected. The second factor to consider is electrical to optical efficiency. This factor also varies widely depending on the technology used to generate and control the laser beam. The third factor is that of loss and beam spread over distance. This factor can be modeled by examining the affect on the laser beam of the media through which the laser is transmitted.

The starting point in understanding the physics of loss and beam spread is defining some terms. Irradiance is a measure of power density or energy over a two dimensional area. For a laser with the output power P_0 and a beam with a two dimensional area of A, the peak irradiance I_p at the target of the laser is shown by equation (1.4).

$$(1.4) \quad I_p = \frac{P_0 \tau}{A}$$

Where atmospheric transmittance is τ. Minimizing the area at the target or maximizing the product of power output and transmittance will maximize irradiance. Now consider beam propagation in a vacuum. The intensity profile of most laser beams is Gaussian transverse to the beam. The beam radius w is defined as the distance from the center of the Gaussian peak out to where the intensity has fallen to $1/e^2$ (0.13533) of the peak value. The beam waist is the point of the beam with the smallest area and is usually very close to the output of the laser The beam radius, w, varies as a function of the waist of the beam as shown in equation (1.5).

$$(1.5) \quad w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

Where wavelength is λ, z is the distance from the waist of the beam to the target and w_0 is the radius of the laser at the beam waist. Using this information and the equation for the area of a circle we arrive at the equation (1.6).

$$(1.6)\quad A = \pi w(z)^2$$

From this it is clear that by using a smaller wavelength as well as increasing the radius of the beam waist that the tendency of the beam to diffract can be reduced. The wavelength a laser transmits depends on the type of laser being used but is confined to the electromagnetic visual spectrum and the areas just outside the visual like ultraviolet and infrared. The beam waist itself can be increased using lenses in what is known as a beam expander. Now with the equations above the area of the laser beam at the target can be found. Returning to equation (1.4) we need to deal with transmittance that is a function of the medium through which atmospheric effects.

The attenuation of a laser by the atmosphere is described by Beer's Law as shown in equation (1.7). where γ is the attenuation coefficient, z is again the length of the transmission path and τ is the transmittance.

$$(1.7)\quad \tau = \frac{I(z)}{I(0)} = \exp(-\gamma z)$$

It can be seen that fundamentally transmittance is simply a ratio of the energy transmitted I(0) and the energy received I(z). Four processes combine to equal the attenuation coefficient: aerosol absorption, aerosol scattering, molecular absorption and molecular scattering. These can be calculated analytically however previously performed experiments and modeling can be informative. Figure 2 shows experimental data of atmospheric transmittance as measured over an 1820 m horizontal path at sea level. Similarly Figure 3 shows how the broad spectrum of solar radiation is attenuated by the atmosphere and the % absorption at given frequencies. Table 1 shows the atmospheric windows where the least attenuation occurs (Weichel, 1990).

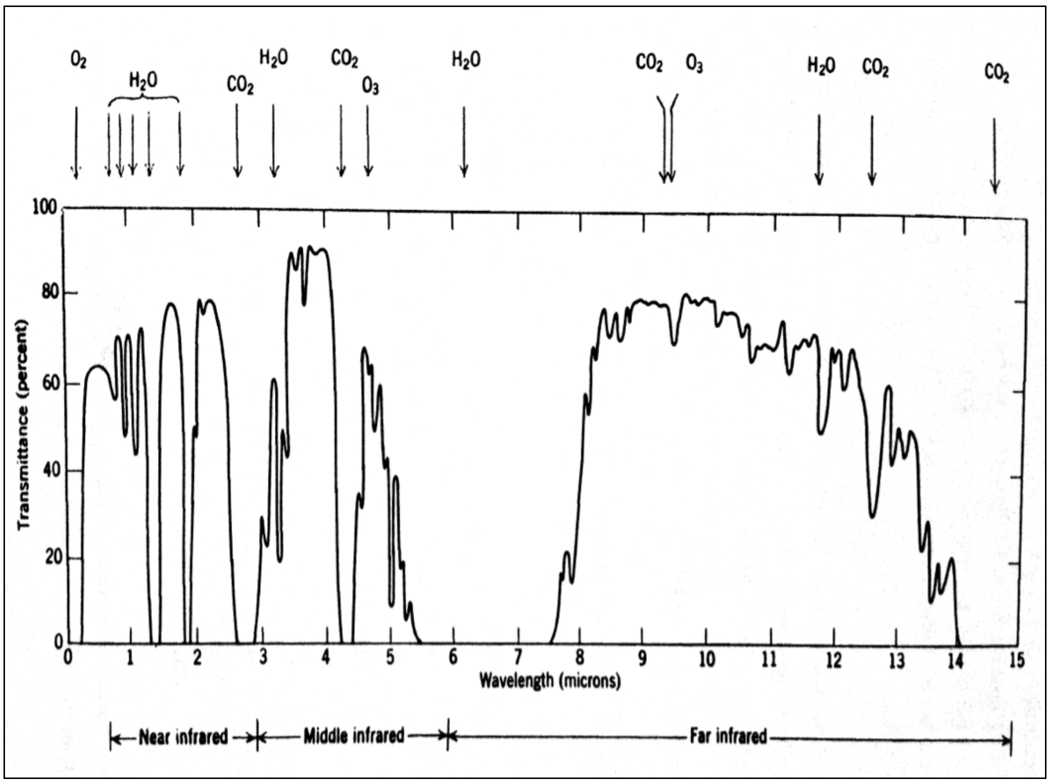

Figure 2. Atmospheric transmittance measured over 1820m horizontal path at sea level (From Weichel, 1990)

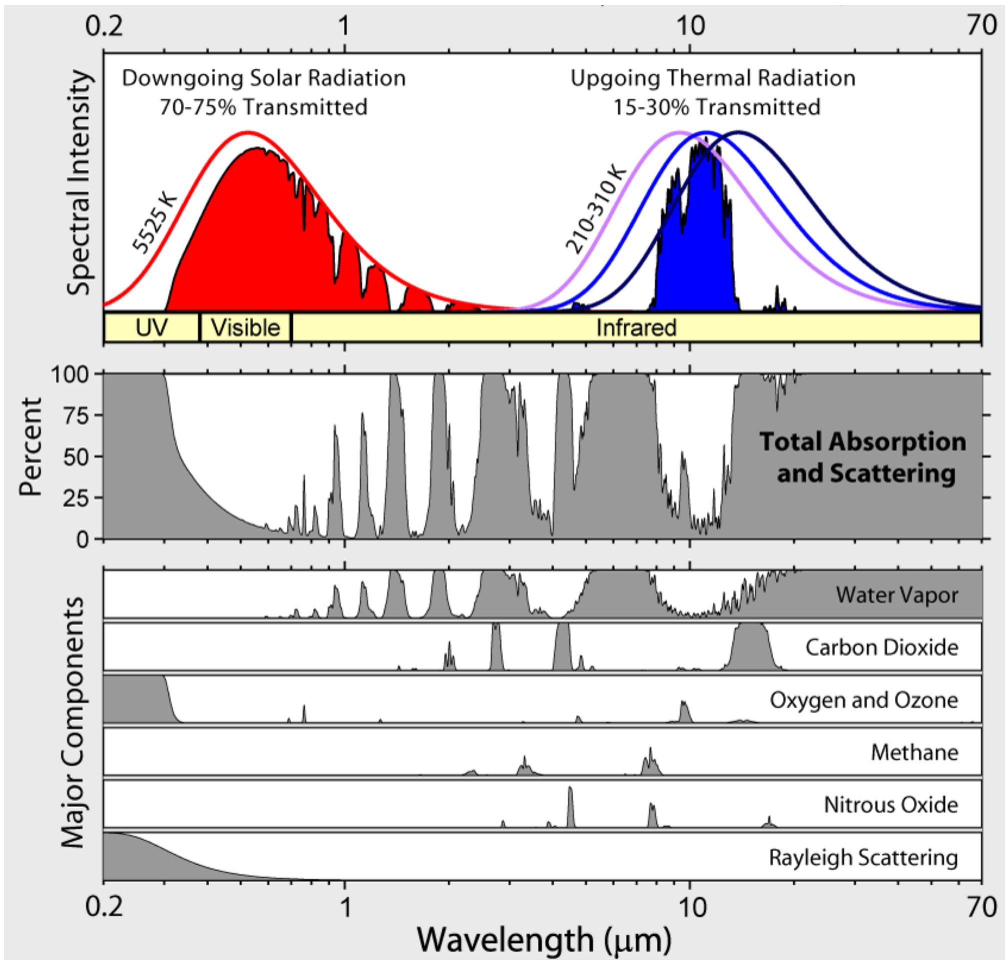

Figure 3. Radiation Transmitted through the Atmosphere (From Rohde, 2007)

Window Number	Window Boundaries (µm)	
	Low	High
I	0.72	0.94
II	0.94	1.13
III	1.13	1.38
IV	1.38	1.90
V	1.90	2.70
VI	2.70	4.30
VII	4.30	6.0
VIII	6.0	15.0

Table 1. Wavelength Boundaries for Atmospheric Windows (From Weichel, 1990)

4. High Irradiance Photovoltaic

Being able to continuously convert high intensity energy near the infrared spectrum into electricity is a technology in current research. One approach is to use photovoltaic cells to directly transform optical energy into electrical energy. Most photovoltaic cells have been designed to perform in applications where the incoming energy is in the form and intensity of the broadband light given off by the sun. Applications where optical energy is concentrated to an intensity far exceeding that of one sun's irradiance will require new receiver designs. Such a receiver has been developed based on a Vertical Multi-Junction (VMJ) photovoltaic cell (Nayfeh, Fast, Raible, Dinca, Tollis, & Jalics, 2011).

The VMJ cell is a bonded series-connected array of miniature silicon junction unit cells (Goradia & Sater, 1977). Because the cell itself is build up as a stack and contains an array of unit cells a small 40 junction VMJ cell (0.8 cm^2 area) can output 24 Volts. The same size VMJ cells have been flashed with 2500 times solar irradiance (or 211W/cm^2) and were able to produce 40.4 W electrical output. This is an electrical conversion efficiency of 23% (Nayfeh, Fast, Raible, Dinca, Tollis, & Jalics, 2011).

The issues of using a VMJ cell to convert optical energy to electricity on a continuous basis are in two main areas. The first is dealing with the unconvertible energy which is transformed largely into thermal energy. For terrestrial based systems a heat rejection system comprised of traditional heat pipes using an evaporative working fluid could be employed. The second issue is the requirement for VMJ cells to be under uniform illumination. This requirement exists due to the series nature of the integration of the VMJ cell in which the unit cell that receives the lowest illumination effectively limits the entire cell's performance (Nayfeh, Fast, Raible, Dinca, Tollis, & Jalics, 2011).

When the same VMJ cell described above was integrated with a system built to deal with thermal rejection and placed in an experimental setup that minimized illumination variance the cell was able to continuously generate 6.24W with an input radiant power of 27.1W. These results could be scaled as long as the heat dissipation could be managed (Nayfeh, Fast, Raible, Dinca, Tollis, & Jalics, 2011).

C. GLOBAL ELECTRICAL POWER

This research is fundamentally focused on transporting electrical power from where it is plentiful to where it is not. This section focuses on clarifying the global environment of electrical power availability and accessibility. Table 1 shows electrification rates in the developing world. The area of lowest electrification is Sub-Saharan Africa with a total electrification of 30.5% and a rural rate of only 14.2% that equates to 585 million people without access to electricity in that region alone. As a reference point, in the United States, electrical power generation is at 1.52 kW per person for a total amount of electricity of 4.12 trillion kW hours per year. Figure 4 shows a plot of electrification rates versus total population without electricity for the least advantaged countries (Wolfram Alpha, 2012). Figures 5, 6, 7 and 8 show a graphical depiction of electrical power generation in Africa, parts of Asia and South America. Tables 2, 3 and 4 show the per capita power generation in all countries in Africa, Asia and South America.

	Population without electricity million	Electrification rate %	Urban electrification rate %	Rural electrification rate %
Africa	**587**	**41.8**	**68.8**	**25.0**
North Africa	2	99.0	99.6	98.4
Sub-Saharan Africa	585	30.5	59.9	14.2
Developing Asia	**675**	**81.0**	**94.0**	**73.2**
China & East Asia	182	90.8	96.4	86.4
South Asia	493	68.5	89.5	59.9
Latin America	31	93.2	98.8	73.6
Middle East	21	89.0	98.5	71.8
Developing countries	**1,314**	**74.7**	**90.6**	**63.2**
World*	**1,317**	**80.5**	**93.7**	**68.0**

Table 2. 2009 World Electrification Rates (From International Energy Agency, 2010)

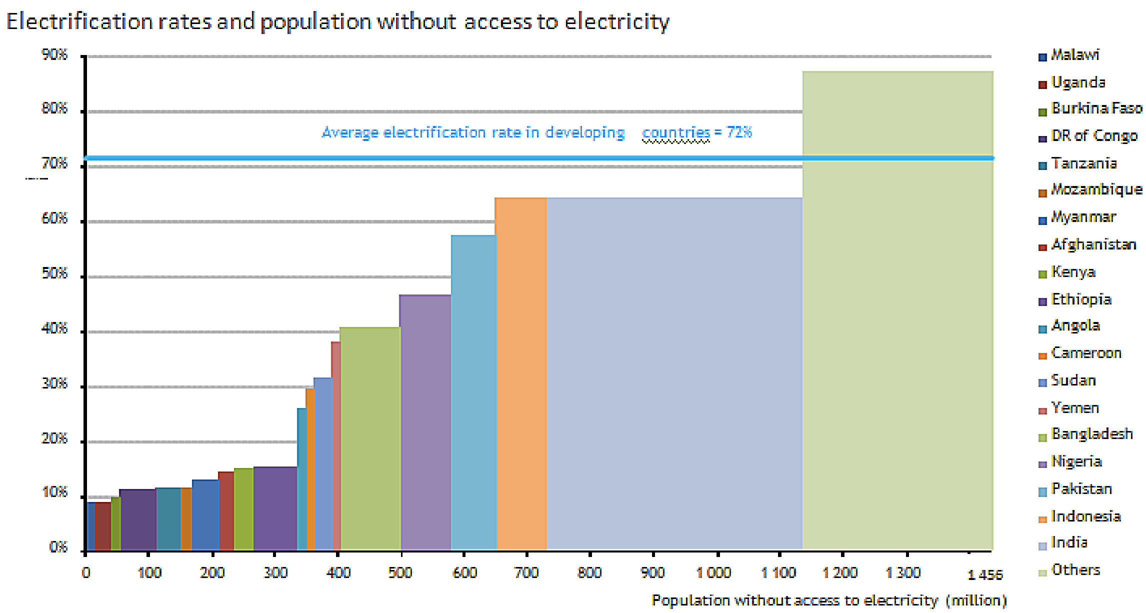

Figure 4. Electrification rates and population without access to electricity (From International Energy Agency, 2010)

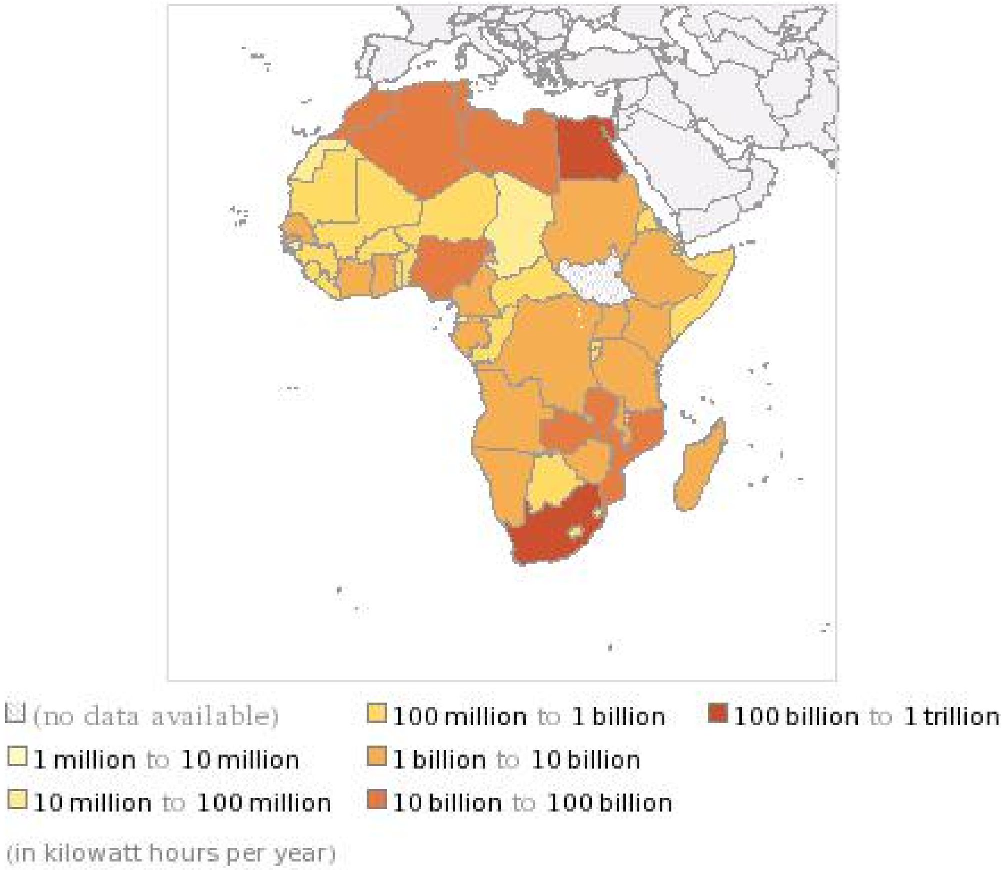

Figure 5. Electricity generation in Africa (From Wolfram Alpha, 2012)

1	South Africa	0.525 kW/person
2	Libya	0.499 kW/person
3	Seychelles	0.329 kW/person
4	Réunion	0.287 kW/person
5	Mauritius	0.254 kW/person
6	Egypt	0.185 kW/person
7	Tunisia	0.162 kW/person
8	Algeria	0.13 kW/person
9	Gabon	0.122 kW/person
10	Saint Helena	0.119 kW/person
11	Zambia	0.0879 kW/person
12	Mozambique	0.0819 kW/person
13	Morocco	0.0708 kW/person
14	Zimbabwe	0.0688 kW/person
15	Namibia	0.0668 kW/person
16	Cape Verde	0.0616 kW/person
17	Djibouti	0.0455 kW/person
18	Swaziland	0.0427 kW/person
19	Ghana	0.0411 kW/person
20	Cameroon	0.032 kW/person
21	Ivory Coast	0.0293 kW/person
22	Western Sahara	0.0247 kW/person
23	Angola	0.0245 kW/person
24	Botswana	0.0241 kW/person
25	Senegal	0.0231 kW/person
26	São Tomé and Príncipe	0.0221 kW/person
27	Kenya	0.0184 kW/person
28	Mauritania	0.0161 kW/person
29	Equatorial Guinea	0.016 kW/person
30	Gambia	0.0156 kW/person
31	Republic of the Congo	0.0152 kW/person
32	Nigeria	0.0136 kW/person
33	Democratic Republic of the Congo	0.013 kW/person
34	Malawi	0.0126 kW/person
35	Sudan	0.0115 kW/person
36	Tanzania	0.0114 kW/person
37	Lesotho	0.011 kW/person
38	Guinea	0.0106 kW/person
39	Liberia	0.00932 kW/person
40	Comoros	0.00859 kW/person
41	Uganda	0.00826 kW/person
42	Madagascar	0.00765 kW/person
43	Eritrea	0.00605 kW/person
44	Ethiopia	0.00543 kW/person
45	Burkina Faso	0.00466 kW/person
46	Guinea-Bissau	0.00451 kW/person
47	Mali	0.00446 kW/person
48	Central African Republic	0.00405 kW/person
49	Somalia	0.00384 kW/person
50	Rwanda	0.00267 kW/person
51	Sierra Leone	0.00235 kW/person
52	Togo	0.00207 kW/person
53	Burundi	0.0017 kW/person
54	Niger	0.00151 kW/person
55	Benin	0.00149 kW/person
56	Chad	9.43×10^{-4} kW/person

Table 3. Africa Per Capita Power Generation (From Wolfram Alpha, 2012)

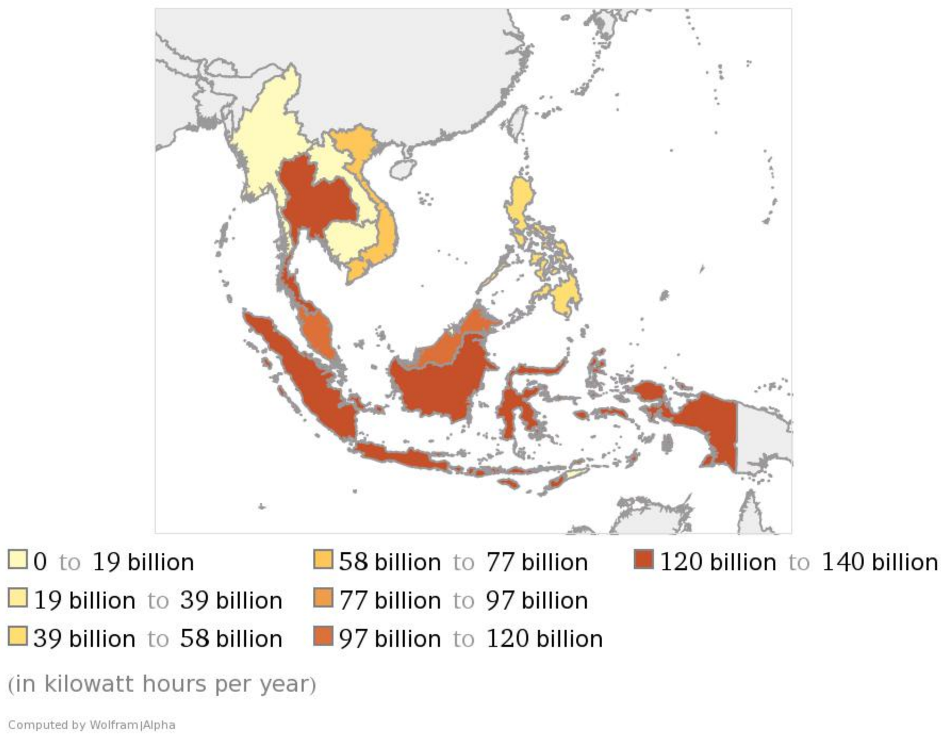

Figure 6. Electricity generation in Southeast Asia (From Wolfram Alpha, 2012)

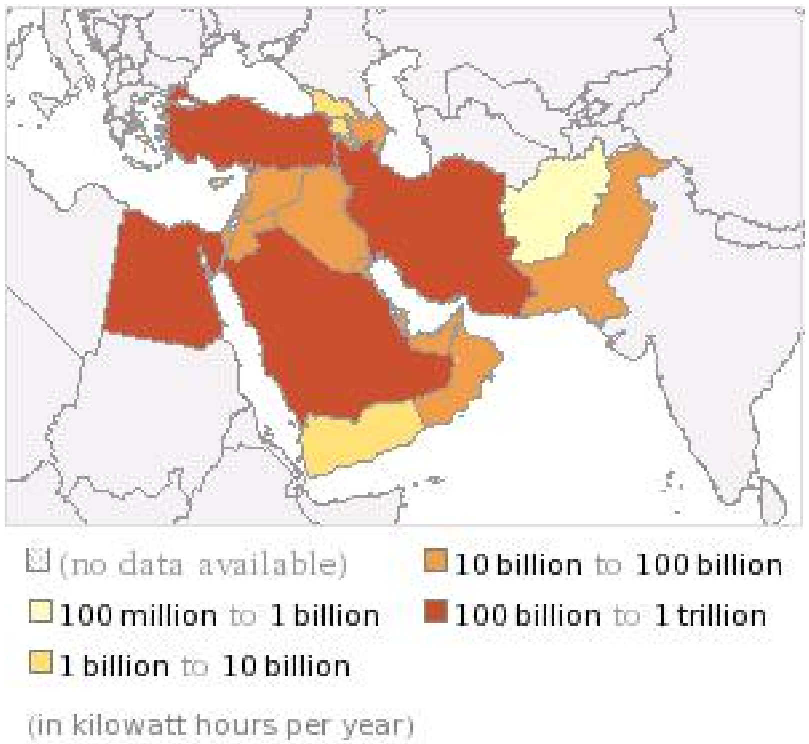

Figure 7. Electricity generation in Southwest Asia (From Wolfram Alpha, 2012)

1	United Arab Emirates	2.02 kW/person	26	Jordan	0.237 kW/person
2	Kuwait	1.92 kW/person	27	Azerbaijan	0.228 kW/person
3	Qatar	1.69 kW/person	28	Georgia	0.228 kW/person
4	Bahrain	1.6 kW/person	29	Kyrgyzstan	0.225 kW/person
5	Bhutan	1.1 kW/person	30	Syria	0.207 kW/person
6	South Korea	1.06 kW/person	31	Armenia	0.202 kW/person
7	Taiwan	1.06 kW/person	32	Uzbekistan	0.195 kW/person
8	Singapore	1.01 kW/person	33	Mongolia	0.171 kW/person
9	Brunei	0.952 kW/person	34	Iraq	0.148 kW/person
10	Saudi Arabia	0.923 kW/person	35	Maldives	0.109 kW/person
11	Japan	0.911 kW/person	36	Vietnam	0.102 kW/person
12	Israel	0.839 kW/person	37	North Korea	0.0973 kW/person
13	Russia	0.8 kW/person	38	India	0.0827 kW/person
14	Oman	0.73 kW/person	39	Philippines	0.0782 kW/person
15	Hong Kong	0.581 kW/person	40	Indonesia	0.0766 kW/person
16	Kazakhstan	0.56 kW/person	41	Laos	0.0661 kW/person
17	Malaysia	0.458 kW/person	42	Pakistan	0.0545 kW/person
18	Lebanon	0.348 kW/person	43	Sri Lanka	0.0531 kW/person
19	China	0.334 kW/person	44	Yemen	0.0298 kW/person
20	Turkmenistan	0.331 kW/person	45	Bangladesh	0.0248 kW/person
21	Iran	0.325 kW/person	46	Myanmar	0.0129 kW/person
22	Turkey	0.303 kW/person	47	Nepal	0.0118 kW/person
23	Macau	0.293 kW/person	48	Cambodia	0.00862 kW/person
24	Tajikistan	0.257 kW/person	49	Afghanistan	0.00358 kW/person
25	Thailand	0.248 kW/person	50	East Timor	0 kW/person

Table 4. Asia Per Capita Power Generation (From Wolfram Alpha, 2012)

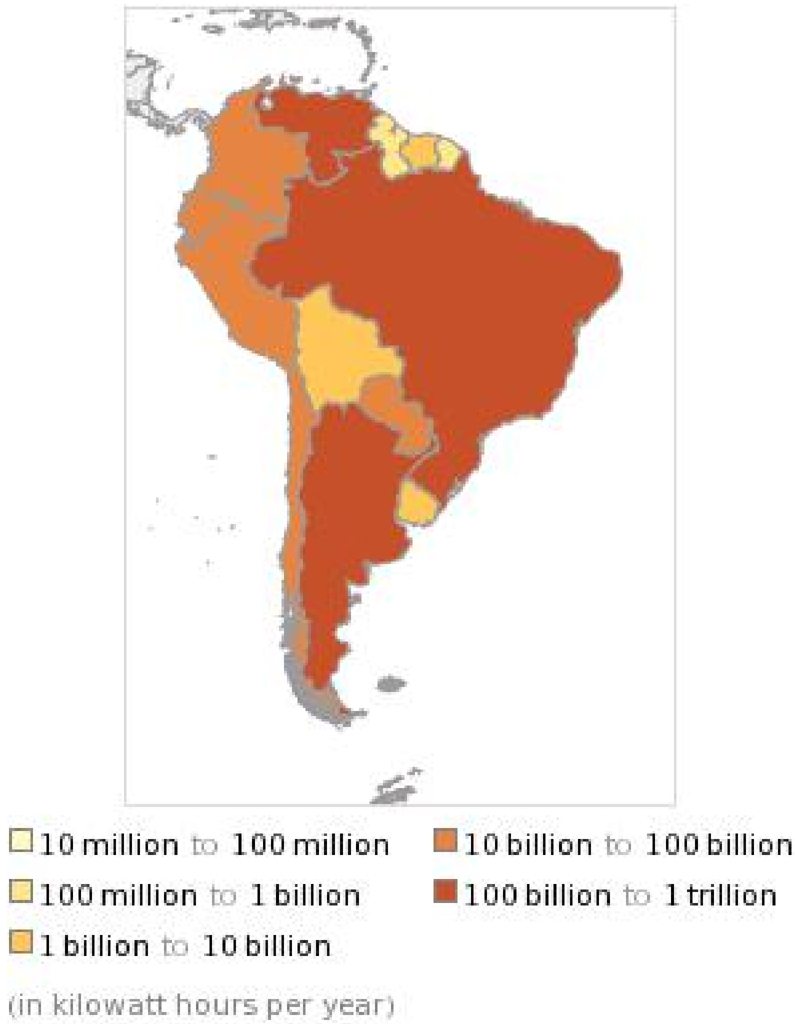

Figure 8. Electricity Generation in South America (From Wolfram Alpha, 2012)

1	Paraguay	0.961 kW/person
2	Falkland Islands	0.691 kW/person
3	Venezuela	0.415 kW/person
4	Chile	0.398 kW/person
5	Suriname	0.349 kW/person
6	Argentina	0.326 kW/person
7	Brazil	0.286 kW/person
8	Uruguay	0.266 kW/person
9	French Guiana	0.212 kW/person
10	Colombia	0.139 kW/person
11	Ecuador	0.138 kW/person
12	Peru	0.126 kW/person
13	Guyana	0.123 kW/person
14	Bolivia	0.0668 kW/person

Table 5. South America Per Capita Power Generation (From Wolfram Alpha, 2012)

Although there are hundreds of millions of humans who do not have access to electricity and numerous countries where the electrification rates are particularly low the data shows that commercial power is obtainable worldwide. The infrastructure and economics that enable the delivery of that power are not always in place, especially outside of urban centers.

D. EXPEDITIONARY ELECTRICAL INFRASTRUCTURE

1. Introduction

In order to understand the electricity requirements of the architectures postulated in Chapter III, it is necessary to understand how the existing electricity infrastructure, with which modern U.S. expeditionary forces are deployed. This deployed infrastructure has three elements. The first element is generation, where fossil fuels are converted into

high voltage alternating current electricity. The second is the high-voltage primary distribution element, where, electricity from one generator can be combined with the electricity from others and distributed up to a mile to secondary distribution. The third and final element is the low-voltage secondary distribution element, which transforms high voltage electricity to a usable voltage and transports it short distances to the end user (United States Air Force, 2008).

2. Conventional Electricity Generation

The military has fielded a scalable system know as the Deployable Electricity Generation and Distribution System (DPGDS) that consists of tactical quiet generators of various electricity output levels. These generators range in size from the largest single generator the MEP-12 that generates 750kW at 2400/4160 Volts (2400 Volts line-to-neutral; 4160 Volts line-to-line) to the smallest the MEP-804A that is rated at 15 kW at 120/208 Volts or 240/416 Volts. The key capability of the generation element is that it has the ability to scale electricity production from just a few kW all the way to near the mega-watt range and operate with the same distribution systems (United States Air Force, 2008).

3. Distribution

The DPGDS has two elements dedicated to distribution. The first is the primary switch center, which combines and routes high voltage electricity (2400/4160 Volt) from generators to secondary distribution. Having electricity at high voltage increases transmission efficiency over larger distances, which in the context of an expeditionary base allows one set of generators to service facilities up to a mile distant. The secondary distribution center acts as a transformer that can convert from 2400/4160 Volts to 120/208 Volts, the level used by most equipment. The secondary distribution center also acts as a distribution hub with the ability to feed up to 16 power distribution panels. Power distribution panels are the terminuses to which facilities or equipment connects to receive electricity (United States Air Force, 2008).

E. EXPEDITIONARY BASING

The U.S. military engages in two major categories of basing of its forces. The first category is permanent basing which are sites where the U.S. plans to have a long term presence. These locations generally use permanent construction standards and receive their electricity from commercial providers. The second major category is contingency basing where the facility is intended to support immediate but temporary operations. These locations can be large enough to support tens of thousands of forces that operate over a large area, and have advanced infrastructure. Contingency bases can also be small and merely support a few hundred forces that are capable of quick response to local operations, security, civic assistance or humanitarian relief. These contingency bases tend to have stark infrastructures that are dependent on larger bases for logistics. The smallest contingency base facility planning categories is the Contingency Operating Location (COL), occupied by a battalion sized unit (300–1000 soldiers) (About.com, 2012). This size of base is authorized only the most essential facility types. Each base has a particular mission and is configured to support it however regardless of the mission only certain types of facilities are authorized. Figures 9, 10, and 11 show the specific facilities authorized for a COL.

FACILITY	Contingency Operating Base (COB)	Contingency Operating Site (COS)	Contingency Operating Location (COL)
Roads*	YES	YES (only gravel)	YES (only gravel)
DFAC	YES	YES	NO
Housing	YES	YES	YES (Tents Only)
Latrines and Septic Systems	YES	YES	YES (portable)
Shower	YES	YES	YES
Office	YES	YES	YES (Tents Only)
SSA/Warehouse	YES	NO	NO
DX/CIF	YES	NO	NO
Finance and Personnel Support Operations	YES	Operationally Defined	NO
Postal Facility	YES	NO	NO
Laundry Collection/Distribution Point	YES	YES	NO
Helipad	YES	YES	Operationally Defined
Runway and Taxiway	YES	NO	NO
Aviation Fuel	YES	Operationally Defined	NO
Squadron Operations Building	YES	NO	NO
Aviation Maintenance	YES	Operationally Defined	NO
Communications Compound/NSC	YES	Operationally Defined	NO
Medical	YES	YES (Aid Stations)	MEDICS

Figure 9. Authorized Facility Table (From United States Central Command, 2009)

FACILITY	Contingency Operating Base (COB)	Contingency Operating Site (COS)	Contingency Operating Location (COL)
Vehicle Maintenance	YES	YES	NO
Ground Fuel	YES	YES	NO
Hazardous Waste Collection Point	YES	YES	NO
Hazardous Materials Warehouse	YES	NO	NO
Parking Lots	YES	YES	Operationally Defined
DS Maintenance	YES	NO	NO
Kennel	YES	Operationally Defined	Operationally Defined
Morgue	YES	NO	NO
DRMO	YES	NO	NO
ASP	YES	NO	NO
BLAHA/CAHA	YES	NO	NO
Wash Rack	YES	NO	NO
Fire Protection	YES	YES (but different level)	YES (but different level)
Training Facilities	YES	NO	NO
MP Station	YES	Operationally Defined	NO
ASG	YES	NO	NO
Cold Storage	YES	Operationally Defined	NO
Chapel	YES	NO	NO
Education Center	YES	YES (combined with Community	NO

Figure 10. Authorized Facility Table continued (From United States Central Command, 2009)

FACILITY	Contingency Operating Base (COB)	Contingency Operating Site (COS)	Contingency Operating Location (COL)
		Activities)	
Barber/Beauty Shop	YES	YES	NO
Alteration/Pressing Shop	YES	NO	NO
PX	YES	YES	AAFES Trailer
PX Warehouse	YES	NO	NO
Fitness Center	YES	YES	YES (Tents Only)
Field House/Multipurpose Facility	YES	YES	NO
Athletic Fields	YES	YES (limited)	NO
Community Activity Center	YES	YES (combined with Education Center)	YES (Tent Only for Recreation/Break Room)
Multi-Purpose Theater	YES	NO	NO
MWR Warehouse/Maintenance Facility	YES	NO	NO
AFN Manned Operations	YES	NO	NO
AFN Unmanned Operations	YES	YES	NO

* "Roads" include roads, streets, open storage areas and parking areas.

Figure 11. Authorized Facility Table continued (From United States Central Command, 2009)

There are also three levels of construction standards that are based on the duration a particular base is likely to exist. The three levels are initial, for bases meant to exist less than six months; temporary for those planned to exist from 6 to 24 months and finally semi-permanent for the few bases intended to operate for 2 to 25 years (United States Central Command, 2009). Figures 12, 13 and 14 show what kinds of facilities are authorized for the initial and temporary levels of construction (United States Central Command, 2009).

Facility	Initial (< 6 months)	Temporary (6 months to <24 months)
Housing+	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts#
Latrine	Burn out or Chemical	AB units/SEAhut
Shower	Shower Unit Tent	AB units/SEAhut
Sewage Disposal	Leech Field or Lagoon	Lagoon/Treatment Plant
Office**	Unit or BEAR-FP Tents	SEAhut# or Container
Helipad	Stabilized Earth or AM2 Matting	Concrete
Fuel	Bladder	Bladder
Vehicle Maintenance**	Unit or BEAR-FP Tents	Clamshell
Vehicle hard stands	Stabilized Earth or Gravel	Concrete
Medical***	Unit or Medical Tents	BEAR-FP Tents to SEAhuts
Morgue**	Unit Tents or Refrigerated Containers	SEAhut or Container
Kennel	Container if needed	Container (incl exercise area)

Figure 12. Contingency Base Camp Standards, Support Facilities (From United States Central Command, 2009)

Storage**	Unit Tents or MILVANs	MILVANs
DRMO	Unit or BEAR-FP Tents	Metal Prefab concrete or asphalt floor, Gravel holding area
Roads/Streets	Stabilized Earth or Gravel	Gravel
Potable Water	Bottled or ROWPU	Well, Treatment Plants
Non-Potable Water	Local Source	Local Source
Wash Rack	Gravel if needed	Gravel
Electric	Unit Generators or Prime Power or Contract	Local Power, Gen Back Up
DFAC**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts#
Ed Center++	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts#
Post Office**	Unit or BEAR-FP Tents	Metal Prefab
PX / Warehouse**	Unit or BEAR-FP Tents	Metal Prefab
Barber**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts
Alteration/Pressing**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts
Laundry**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts
Fire	Unit or BEAR-FP Tents	Metal Prefab
Fitness Center**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts#

Figure 13. Contingency Base Camp Standards, Support Facilities Continued (From United States Central Command, 2009)

Field House**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts
Athletic Fields	None	Open Fields
Community Center	Unit or BEAR-FP Tents	Metal Prefab
Theater**	Unit or BEAR-FP Tents	Metal Prefab
Chapel**	Unit or BEAR-FP Tents	BEAR-FP Tents to SEAhuts#
MSA	Berms/Wire/Gds	Berms/Wire/Barriers/Gds
Solid Waste	Field Incinerator	Incinerator/Civilian Contract
Medical Waste	Field Incinerator	Incinerator/Civilian Contract
Hazard Waste	Removal from Theater	Civilian Contract
Perimeter Fence	Triple Standard	Triple Standard with Berms
Perimeter Lights	Gen Sets	Fixed Lighting
Guard Towers	None	Standardized Design
Entry points	Berms/Serpentine	Hesco /Concrete Barriers
Detainee Facility	Tents/Wire/Towers	SEAhut#/Chainlink/Towers
EOD**	Unit or BEAR-FP Tents	Metal Prefab
Facility Engineers	Military Units	Military or Civilian Contract
Fire Fighting	Firefighting Eng	Military or Civilian Contract
Snow Removal	Military Units	Military or Civilian Contract
Utilities		
Electrical	Gen Sets/Commercial	Gen Sets/Commercial/Power plants (Plan 125% load capacity)
Environmental	Organic	Organic/Commercial
Control (Heat/Air)		Priority: 1) Mission 2) Medical 3) DFAC 4) Billets 5) Others

Figure 14. Contingency Base Camp Standards, Support Facilities Continued (From United States Central Command, 2009)

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III. SYSTEM ARCHITECTURES

A. INTRODUCTION

In order to postulate, analyze and compare a pair of space based, electricity relay alternatives it is necessary to define the set of system requirements against which performance is compared. The requirement generation and analysis approach is adapted from class notes and a class project conducted during two Naval Postgraduate School courses SS3041 and SS4051 (Space Systems and Operations I and II), as well as the Space Mission Analysis and Design text by Larson and Wertz, and the Applied Space Systems Engineering text by Larson, Kirkpatrick, Sellers, Thomas and Verma.

B. REQUIREMENTS

1. User Identification

The primary user of this system will be U.S. ground forces or ground elements of Naval and/or Air Forces which are operating bases in hostile and/or remote territory with forces on the order of U.S. Army battalion strength (300–1000 personnel). Secondary users are U.S. government agencies operating in humanitarian relief operations of similar size (less than 500 personnel).

2. Stakeholder Requirements

The need for electrical power at forward operating bases is currently being met by the use of on-site generation using fossil fuels. The user requires a system that will meet electricity needs at remote bases safely with minimum ground supplied fuel in a cost effective manner.

3. System Inputs, Outputs and Functional Requirements

A tool that can be used to examine the interplay between inputs and system elements is a use case diagram. Figure 15 shows the inputs and outputs of a generalized system operating in a use case where power is transferred via wireless means from a commercial source through a space segment to a targeted ground receiver and ultimately

to the user's electrical distribution grid. Figure 15 also shows that there are two principal threads that cross system elements. The first thread is power transmission that fulfills the primary mission of the system in receiving and transmitting electrical power from element to element. The second thread concerns the transmission of targeting coordinates to the space segment.

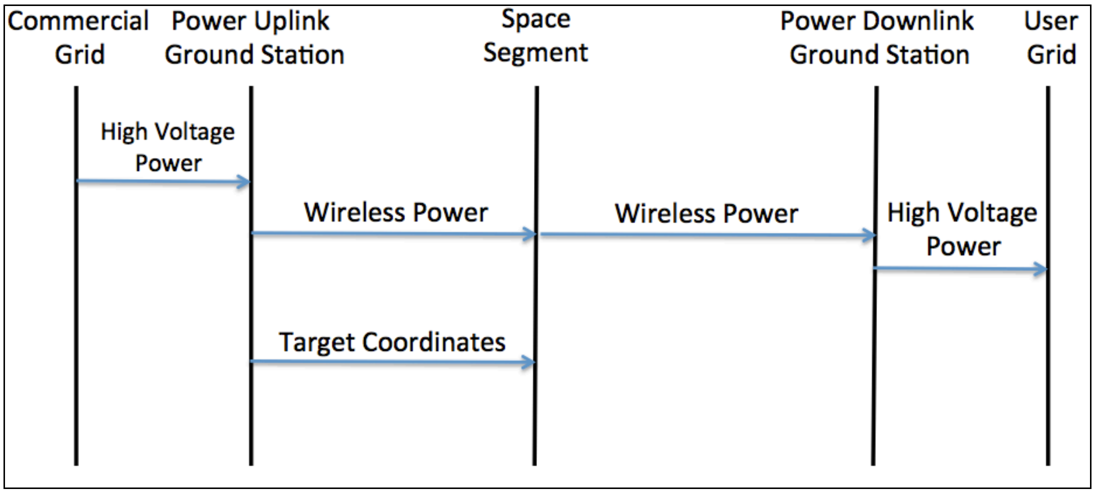

Figure 15. System Inputs and Outputs

With these threads identified it is now possible to establish particular requirements on the system that will drive the design. The first is related to the principal output of the system, electrical power. This system shall have a power output objective of 500 kW and a threshold of 250 kW. Also, for simplicity of analysis purposes, the system shall be required to target a single location per spacecraft for power delivery at any given time.

4. Nonfunctional Requirements

Often the functional requirements are paid more attention than the nonfunctional. This can result in poor system design. Reliability, Availability, and Operability, among others, are often referred together as the "ilities" play a large role in designing a system for real world use (Larson, Kirkpatrick, Sellers, Thomas, & Verma, 2009). Below is a list of the "ilities" and how they will be examined in the context of this system.

a. Reliability: Examine the typical performance levels and component similarity with other systems.
b. Availability: Evaluate the system uptime.
c. Operability: The ease with which the system is operated. This will be looked at qualitatively as a function of effort required by the user and system operator to keep the system working.
d. Transportability: Assess the ability of the system to be fielded. The main component that will be examined for this requirement will be the size of the power downlink in both a mobile context as well as its final deployed configuration.
e. Manufacturability: Assess the difficulty required to produce the key system elements.
f. Safety: Assess the exposure of personnel and equipment to hazard due to system functions.

5. Cost

Cost is a key component in determining the feasibility of the system especially when the system is designed to reduce cost, as this one is intended to do. The two major pieces of cost that will be analyzed are fixed cost and operating cost. The metric associated with operating cost that is often examined in systems designed to deliver power is that of cost per kW/hour and will be used here to inform this analysis. Those elements of cost will be combined and then plotted against the performance so that cost can be analyzed as an independent variable.

C. ANALYSIS PLAN

The analysis of the system will be based on the requirements listed above. A spreadsheet of those requirements will be created and populated with the requirements in a vertical column and the architectures being compared across the horizontal. The requirements will be weighted based on judgment such that those of greater importance are of more influence on the analysis. Requirements will be assessed against the architectures. A justification for those assessments, some quantitative and some qualitative, will be captured on a separate spreadsheet. These assessments will then be populated into the original spreadsheet and totaled for comparison.

D. ARCHITECTURE ATTRIBUTES

The question being asked by this research is whether the use of a space based wireless power relay is feasible. To answer that question the key functional requirement of power delivered to target will be modeled. This section will define the configuration of system elements along the power thread so that they can be placed in the model and analyzed.

1. Architecture A

Architecture A will have the same three major system elements as described in the system inputs and outputs section above. The first, the power uplink ground station will transmit high power EHF RF energy for the uplink. The second system element will be the space segment that will be located in LEO. It will have a rectenna to capture the uplink as well as a high power EHF transmitter for the downlink. At the downlink site there will be another rectenna to complete the power thread. In order to complete the targeting thread the power uplink site will communicate with the relay satellite as it comes over the horizon and task it. Figure 16 shows the operational view of this architecture.

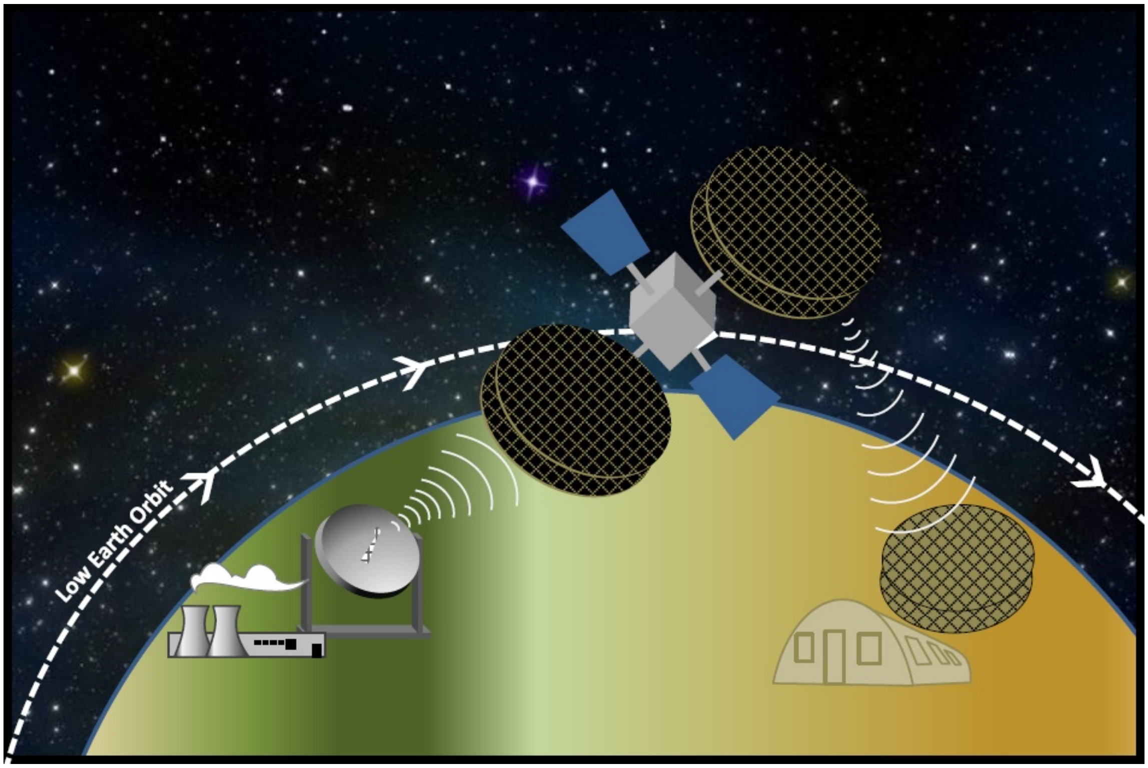

Figure 16. Operational View of Architecture A.

2. Architecture B

This architecture will use lasers instead of RF. The laser operating in the near infrared portion of the spectrum will uplink power to a spacecraft in MEO with a high irradiance photovoltaic receiving array. The space segment power downlink will be accomplished via laser in similar spectrum. The downlink site will use a photovoltaic array to complete the power thread. In order to complete the targeting thread the power uplink site will communicate with the relay satellite as it comes over the horizon and task it. Figure 17 shows the operational view of the architecture.

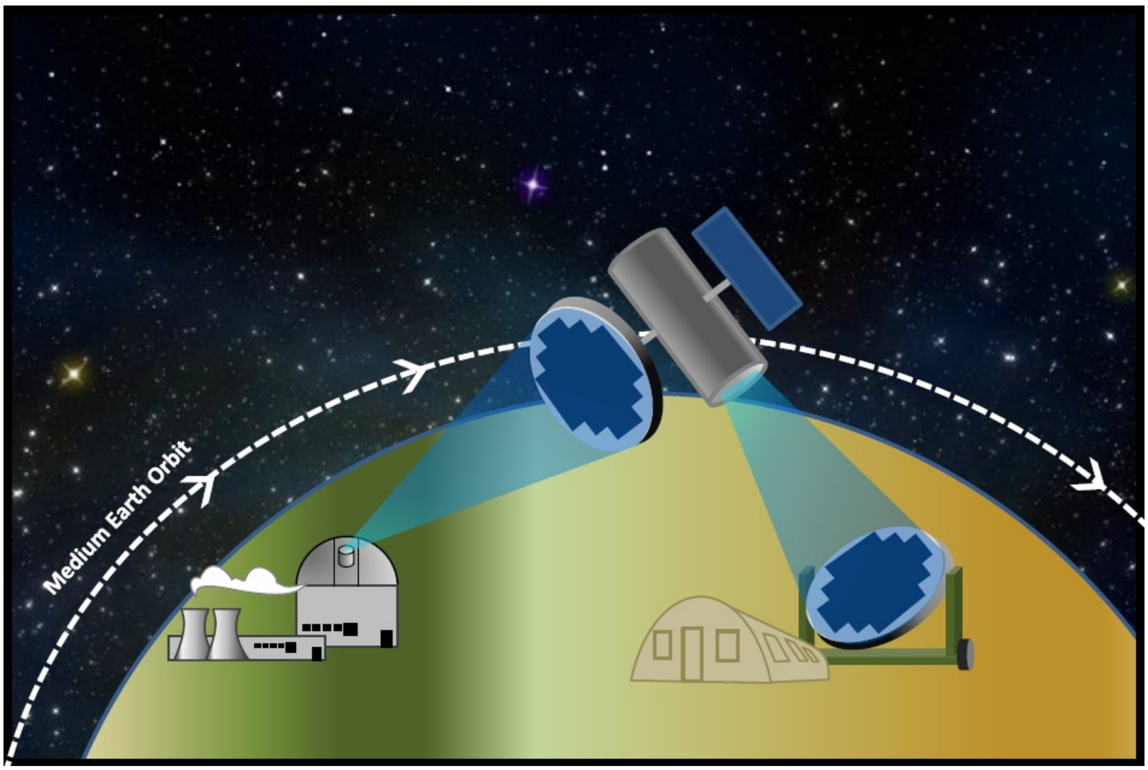

Figure 17. Operational View of Architecture B.

IV. PRESENTATION AND ANALYSIS OF DATA

A. INTRODUCTION

In this chapter, the data collected on the items that were quantitatively analyzed will be shown and described. That data will be combined with knowledge obtained through literature review and placed into the analysis as described in the previous chapter. The purpose here is to show the evidence for the conclusions drawn in the next chapter.

B. ANALYSIS OF ARCHITECTURES

1. End-to-End Power Thread Analysis

This analysis was conducted in order to better understand the end-to-end realities concerning energy loss of the power thread of each architecture. The inputs for this analysis were the orbital altitude, the power delivery requirement and a few assumptions. The assumptions are listed at the start of each set of analysis tables. Analysis started with the delivered power and then moved backwards along the power thread from major element to major element. As the process moved along, the fundamental characteristics of the system were defined. At the end of each architecture's analysis, the power input, the amount of power required by the system in order to deliver the required output was determined. The primary other detail clarified was the physical sizing estimates for the receiving and transmitting apertures within various elements. The final detail that came from this analysis was an estimated cost per kW/h of the power output. Tables 6, 7 and 8 show the analysis process and results for Architecture A and Tables 9, 10 and 11 show the analysis process and results for Architecture B.

Examine Architecture A

Question: 1

How much power is needed at input for the power thread to deliver the objective?

Assumptions:

1. The operating frequency for this system is 94 Ghz
2. The orbit is a Low Earth orbit at 500 km
3. The uplink and downlink path is directly perpendicularto the earth's surface
4. The receive to transmit efficiency of the spacecraft payload is 90%
5. The 30km thickness of the stratosphere will be used as the thickness of the atmosphere for loss calculations
6. Assume the cost of input power is $0.15

Step 1: Optimize the power downlink based on the maximum conversion power density (1 Watt/cm^2) of the receiving rectenna array.

		Value	Unit	
Power Delivered to Target	Power Output	500	kW	A.)
Loss due to conversion efficiency	Efficiency	72%		B.)
	C = A/B	694.44	kW	C.)
Loss due to collection efficiency	Efficiency	93%		D.)
	E = C/D	746.71	kW	E.)

Note: 746.71 kW is the amount of energy the ground site will need to receive in order to output 500 kW.

Step 1.1: Optimize the size of the rectenna receiver

Conversion Density	1	Watt/cm^2	F.)
1 m^2	10,000	cm^2	G.)
E.) in W	746714.46	Watts	H.)
I = H/G	74.67	m^2	I.)

Note: The minimum area of the receiving rectenna is 74.67 m^2.

Table 6. Architecture A. Analysis Part 1

Step 2: Using the optimized groud receiving rectenna array size determined in step 1 find the size of the transmitting antenna.					
	Receiver	J = SQRT(I.*4/PI())	9.75	m	J.)
		Low Earth Orbit	500	km	K.)
		Frequency	94	Ghz	L.)
		Speed of light	3.00E+08	m/s	M.)
	Wavelength	N = C/L	0.0032	m	N.)
Using Equation for main lobe diffraction		2.44 = J*O/(N*K)	399.32	m	O.)
Note: The diameter of the transmitting antenna is shown to need to be 400 meters in diameter… which is a quite large for a spacecraft. The ground receiving antenna however could be significantly larger.					
Step 2.1: Select a more reasonable size for spacecraft transmit antenna diameter. For reference the antennas onboard Thuraya are deployable 12.25 meter antennas.					
	Transmitting antenna diameter	Set to a Thurya analog diameter	12.25	m	P.)
	Receiver diameter	2.44 = P*R/(N*K)	317.8462875	m	R.)
Note: This makes the ground receive diameter 317 meters. This is quite large (19.5 acres), but at this point the limiting factor is the size of the spaceborne antenna, if it could be incresed by even 10 or 20 meters this would greatly decrease the receiver diameter. It should be noted however that given this size of a receiver the rectenna technology is no where near the theoretical maximum conversion density therefore the amount of power which could be received by the ground is on the order of 793 MW (megawatts).					
Step 3: Find the power required to be transmitted by the spacecraft in order to get 746.71 kW to the ground					
		Amount of power in the main lobe of the beam	85%	percent	S.)
		T = E/S	878.49	kW	T.)
		Atmospheric Loss @ 94 Ghz	0.35	dB/Km	U.)
		Stratosphere	30	Km	V.)
	Total Loss	U = S*T	10.5	dB	W.)
		X = 10^(W/10)*T	9856.79	kW	X.)

Table 7. Architecture A. Analysis Part 2

Step 4: Find the power needed to be received by the spacecraft at the rectenna				
	Receive to Transmit efficiency	90%	percent	Y.)
	Z = X/Y	10951.99	kW	Z.)
Loss due to conversion efficiency	Efficiency	72%	percent	AA.)
	(AB) = (Z)/(AA)	15211.10022	kW	AB.)
Loss due to collection efficiency	Efficiency	93%	percent	AC.)
	(AD) = (AB)/(AC)	16356.02174	kW	AD.)
Step 4.1: Optimize the size of the spacecraft rectenna based on the theoretical limit of conversion density				
	Conversion Density	1	Watt/cm^2	AE.)
	1 m^2	10,000	cm^2	AF.)
	746.71 kW	16356021.74	Watts	AG.)
Area	AH = AG/AF	1635.60	m^2	AH.)
Diameter	AJ = SQRT(H*4/PI())	45.63	m	AJ.)
Step 5: Find the power needed to be transmitted such that the main lobe receives a high enough power density to provide the power required.				
	Amount of power in the main lobe of the beam	85%	percent	AK.)
	AL = AD/AK	19242.38	kW	AL.)
	Atmospheric Loss @ 94 Ghz	0.35	dB/Km	AM.)
	Stratosphere	30	Km	AO.)
Total Loss	AP = AM*AO	10.5	dB	AP.)
	AO = 10^(AP/10)*AL	215903.0381	kW	AR.)
Step 5.1: Find the size required of the uplink transmitter aperature such that the main lobe is sized to fit the				
	2.44 =AJ*AS/(N*K)	85.32	m	AS.)
Step 6. Find the cost per kW for electricity delivered via this system				
	Input cost per kW/hour	$0.15	dollars /kW/h	AT.)
	Input to output Ratio	431.8060761	dimensionless	AU.)
	Output cost rate per kw/	$64.77	dollars/kw/h	

Table 8. Architecture A. Analysis Part 3

	Analysis of Architecture B			

Question: 1

How much power is needed at input for the power thread to deliver the objective?

Assumptions:

1. The operating wavelength for this system laser is 1.04 micro-meters in order to take advantage of an atmospheric window.
2. The orbit is Medium Earth Orbit

3. The uplink and downlink path is directly perpendicularto the earth's surface
4. The receive to transmit efficiency of the spacecraft payload is 90%
5. Assume the cost of input power is $0.15

Step 1: Optimize the power downlink based on the maximum conversion power density

		Value	Unit	
Power Delivered to Target	Power Output	500	kW	A.)
Loss due to conversion efficiency	Efficiency	23%		B.)
	C = A/B	2173.91	kW	C.)

Step 1.1: Optimize the size of the Vertical Multi-Junction photovoltaic array.

		Value	Unit	
	Conversion Density	211	Watt/cm^2	F.)
C. in Watts	2173.91	2173913.04	Watts	G.)
	H = G/F	10302.90542	cm^2	H.)
	1 m^2	10,000	cm^2	I.)
Area	J = H/I	1.03	m^2	J.)
Target Radius	K = SQRT(J/PI())	0.57	m	K.)

Note: The minimum area of the receiving VMJ array for the power requirement is 1.03 m^2.

Table 9. Architecture B. Analysis Part 1

Step 2: Use the equation for beam radius at the target and using potential laser beam waist values find what the target radius could be.

		Radius of beam waist	1	m	L.)
		Wavelength	1.04	µm	
			0.00000104	m	M.)
		Distance to target	22000	km	N.)
			22,000,000	m	
Target Radius	O =L*SQRT(1+(M*N/(PI()*L^2))^2)		7.35	m	O.)
		Area = P = PI*O^2	169.7750355	m^2	P.)

Note: The beam waist radius can be varied to reduce the size of the target radius. If the space borne laser radius could be made larger the receive array will approach that same radius. Also if the distance to the array is made smaller the beam spread effect is decreased.

Step 3: Find the power required to be transmitted by the spacecraft in order to get 2173 kW to the ground.

Atmospheric Transmittance @ 1.04 µm	98%	percent	R.)
S = C/R	2218.28	kW	S.)

Step 4: Find the power needed to be received by the spacecraft at Vertical Multi-Junction array

	Receive to Transmit efficiency	90%	percent	T.)
	U = S/T	2464.75	kW	U.)
Loss due to conversion efficiency	Efficiency	23%	percent	V.)
	W = U/V	10716.32182	kW	W.)

Step 4.1: Optimize the size of the spacecraft Vertical Multi-Junction array based on the theoretical limit of conversion density.

	Conversion Density	211	Watt/cm^2	X.)
W. in Watts	10716.32	10716321.82	Watts	Y.)
	Z = Y/X	50788.25505	cm^2	Z.)
	1 m^2	10,000	cm^2	AA.)
Area	AB = Z/AA	5.08	m^2	AB.)
Target Radius	A = SQRT(AB/PI())	1.27	m	AC.)

Table 10. Architecture B. Analysis Part 2

Step 5: Find the power needed to be transmitted such that the target receives a high enough power density to provide the power required.				
	AD = W/R	10935.02	kW	AD.)
Step 5.1: Find the size required of the uplink laser beam waist such that the target beam width is minimized to reduce the need to have a large array on orbit.				
	Radius of beam waist	2.8	m	AE.)
	Wavelength	1.04	µm	
		0.00000104	m	AF.)
	Distance to target	22000	km	AG.)
		22,000,000	m	
Target Radius	AH =AD*SQRT(1+(AF*AG/(PI()*AE^2))^2)	3.82	m	AH.)
	Area = AI = PI*AH^2	45.88435208	m^2	AI.)
Note: At the range given and the wavelength given a beam waist radius of 2.8 meters will minimize the target radius.				
Step 6. Find the cost per kW for electricity delivered via this system				
	Input cost rate per kW/hour	$0.15	dollars/kw/h	AJ.)
	Input to output Ratio	21.87004452	dimensionless	AK.)
	Output cost rate per kw/h	$3.28	dollars/kw/h	

Table 11. Architecture B. Analysis Part 3

2. Coverage and Access Analysis

In order to model the system for availability in STK an example pair of sites were chosen, one for power transmission and one for power receipt. Each power uplink site was modeled with a transmitter and the downlink site with a receiver. Each spacecraft was given one of each a transmitter and a receiver. This allows the STK model of a communications chain to represent the power thread. The power receive location was set at the location of FOB Zeebrugge which is a remote expeditionary base occupied by U.S. Marines. (Ferguson, 2011) In the simulations FOB Zeebrugge is labeled as Afghan1. The power uplink was selected to be at Quetta, Pakistan. It was selected because Pakistan is a cooperative nation with a functional electricity infrastructure in the region of FOB Zeebrugge. The receiver and transmitter at each ground site were elevation limited to 15 degrees. For each architecture the orbital properties of a spacecraft called PowerSat

were defined and the then the transmitter and receiver were placed in a one-way communication chain from Quetta through PowerSat to Afghan1 and an access report was taken for that single chain for the period of 30 days. Figure 18 shows an example of an access chain 3D visualization of a LEO access and Figure 20 shows an example of two simultaneous access chains available to a single spacecraft for the MEO orbit.

For architecture A PowerSat's orbital altitude was set to 500 km with an inclination of 85 degrees. Tables 12 and 13 show the complete chain access report for these orbital elements over 30 days. Using the STK walker function the LEO PowerSat was used to build several constellation configurations with multiple planes and multiple spacecraft per plane attempting to achieve continuous coverage of the target sites. The starting point was inspired by the Iridium constellation of 66 spacecraft in 6 planes. (Iridium, 2012) In order to provide continuous coverage of both ground sites and meet a 24-hour uptime requirement a constellation of 242 spacecraft in an 11 plane by 22 spacecraft per plane configuration was required as shown in Figure19.

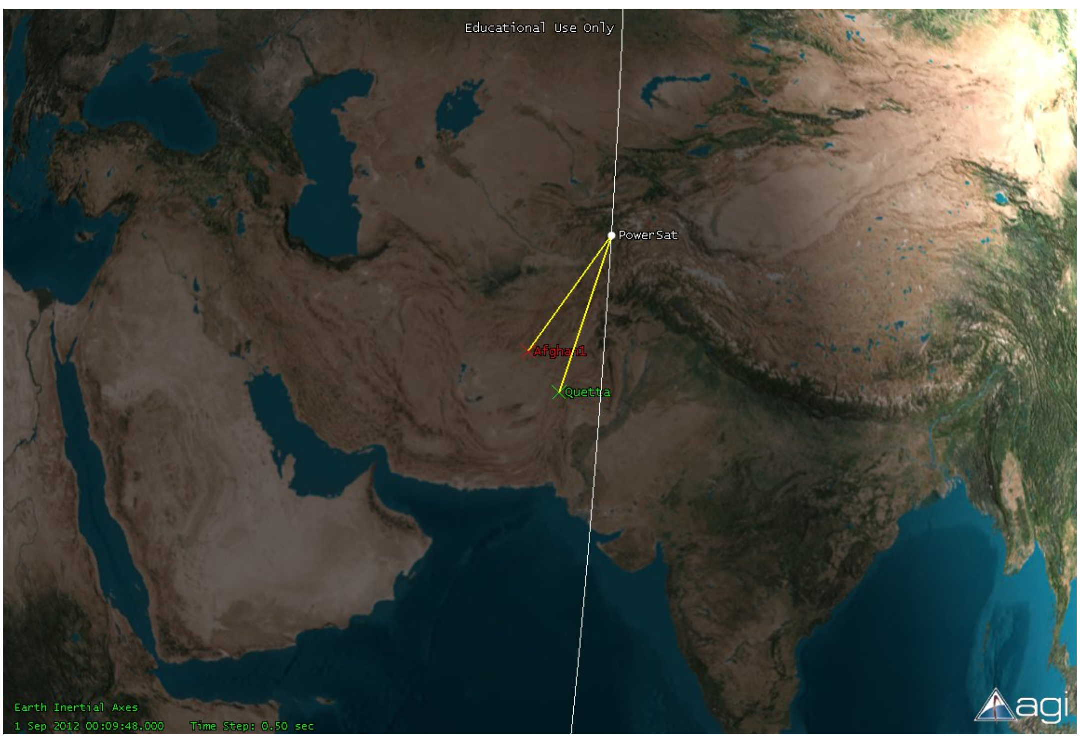

Figure 18. LEO Access between Quetta and Afghan1

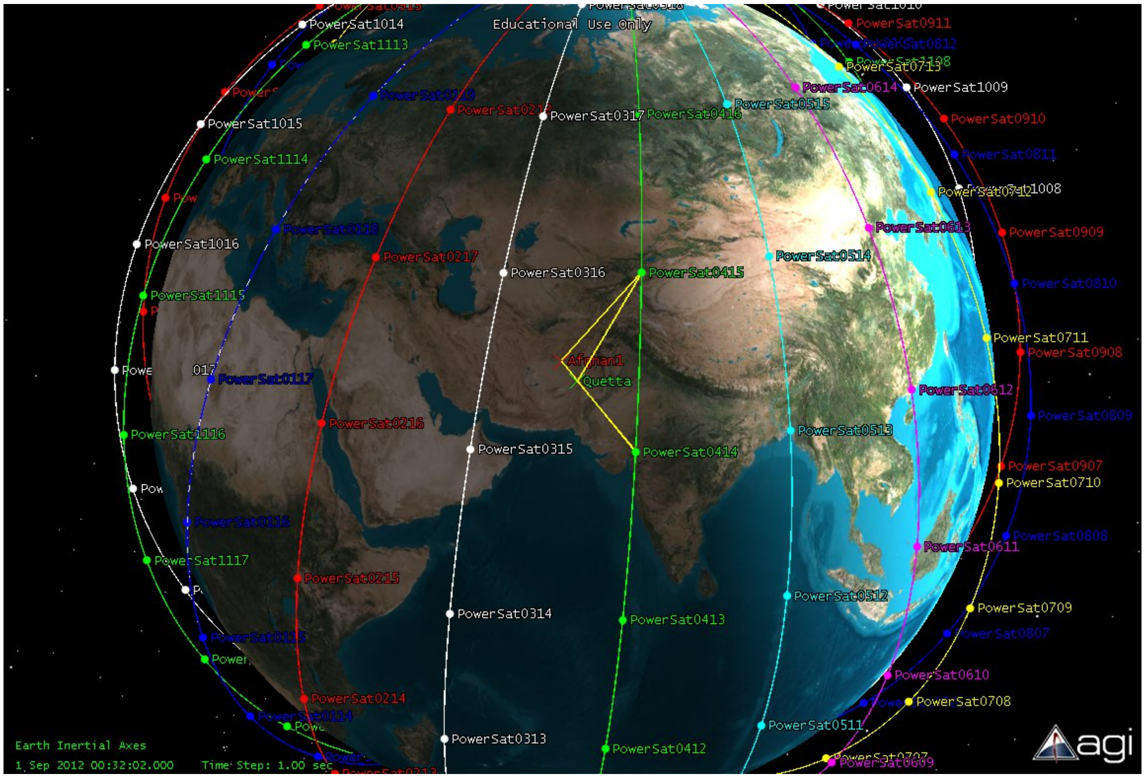

Figure 19. LEO Continuous Coverage Constellation

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Chain-PowerChain: Complete Chain Access

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	1 Sep 2012 00:05:37.107	1 Sep 2012 00:10:56.388	319.281
2	1 Sep 2012 11:39:34.819	1 Sep 2012 11:44:55.763	320.944
3	1 Sep 2012 23:47:07.466	1 Sep 2012 23:51:52.675	285.209
4	2 Sep 2012 11:20:53.295	2 Sep 2012 11:25:44.265	290.970
5	2 Sep 2012 23:28:55.817	2 Sep 2012 23:32:36.907	221.090
6	3 Sep 2012 11:02:23.359	3 Sep 2012 11:06:16.312	232.953
7	3 Sep 2012 23:11:55.163	3 Sep 2012 23:12:12.857	17.695
8	4 Sep 2012 00:45:12.785	4 Sep 2012 00:47:46.514	153.728
9	4 Sep 2012 10:44:20.259	4 Sep 2012 10:46:08.723	108.464
10	4 Sep 2012 12:19:44.879	4 Sep 2012 12:21:54.106	129.227
11	5 Sep 2012 00:25:27.502	5 Sep 2012 00:29:48.414	260.911
12	5 Sep 2012 11:59:52.431	5 Sep 2012 12:04:00.245	247.814
13	6 Sep 2012 00:06:15.051	6 Sep 2012 00:11:22.487	307.435
14	6 Sep 2012 11:40:32.390	6 Sep 2012 11:45:31.604	299.214
15	6 Sep 2012 23:47:14.648	6 Sep 2012 23:52:43.602	328.954
16	7 Sep 2012 11:21:25.961	7 Sep 2012 11:26:50.461	324.499
17	7 Sep 2012 23:28:24.833	7 Sep 2012 23:33:55.326	330.493
18	8 Sep 2012 11:02:29.118	8 Sep 2012 11:07:58.633	329.515
19	8 Sep 2012 23:09:45.883	8 Sep 2012 23:14:58.456	312.573
20	9 Sep 2012 10:43:40.856	9 Sep 2012 10:48:56.088	315.232
21	9 Sep 2012 22:51:20.125	9 Sep 2012 22:55:52.001	271.876
22	10 Sep 2012 10:25:01.998	10 Sep 2012 10:29:40.929	278.931
23	10 Sep 2012 22:33:15.759	10 Sep 2012 22:36:31.915	196.156
24	11 Sep 2012 10:06:36.113	11 Sep 2012 10:10:06.767	210.654
25	11 Sep 2012 23:48:55.273	11 Sep 2012 23:52:10.110	194.837
26	12 Sep 2012 11:23:26.483	12 Sep 2012 11:26:23.369	176.886
27	12 Sep 2012 23:29:24.976	12 Sep 2012 23:34:01.156	276.179
28	13 Sep 2012 11:03:47.458	13 Sep 2012 11:08:12.023	264.566
29	13 Sep 2012 23:10:15.972	13 Sep 2012 23:15:31.180	315.209

Table 12. LEO Complete Chain Access report

	29	13 Sep 2012 23:10:15.972	13 Sep 2012 23:15:31.180	315.209
	30	14 Sep 2012 10:44:31.726	14 Sep 2012 10:49:39.762	308.036
	31	14 Sep 2012 22:51:18.416	14 Sep 2012 22:56:49.634	331.218
	32	15 Sep 2012 10:25:28.037	15 Sep 2012 10:30:55.716	327.680
	33	15 Sep 2012 22:32:31.371	15 Sep 2012 22:37:59.088	327.717
	34	16 Sep 2012 10:06:33.468	16 Sep 2012 10:12:01.137	327.669
	35	16 Sep 2012 22:13:55.549	16 Sep 2012 22:18:59.869	304.319
	36	17 Sep 2012 09:47:47.531	17 Sep 2012 09:52:55.556	308.026
	37	17 Sep 2012 21:55:34.153	17 Sep 2012 21:59:50.421	256.268
	38	18 Sep 2012 09:29:11.564	18 Sep 2012 09:33:36.352	264.788
	39	18 Sep 2012 21:37:39.709	18 Sep 2012 21:40:24.342	164.633
	40	19 Sep 2012 09:10:50.506	19 Sep 2012 09:13:54.257	183.751
	41	19 Sep 2012 22:52:42.944	19 Sep 2012 22:56:29.027	226.083
	42	20 Sep 2012 10:27:14.344	20 Sep 2012 10:30:43.819	209.476
	43	20 Sep 2012 22:33:23.460	20 Sep 2012 22:38:12.580	289.120
	44	21 Sep 2012 10:07:43.905	21 Sep 2012 10:12:22.728	278.823
	45	21 Sep 2012 22:14:17.671	21 Sep 2012 22:19:39.102	321.431
	46	22 Sep 2012 09:48:31.865	22 Sep 2012 09:53:47.119	315.254
	47	22 Sep 2012 21:55:22.906	22 Sep 2012 22:00:55.051	332.144
	48	23 Sep 2012 09:29:30.729	23 Sep 2012 09:35:00.258	329.529
	49	23 Sep 2012 21:36:38.676	23 Sep 2012 21:42:02.258	323.583
	50	24 Sep 2012 09:10:38.412	24 Sep 2012 09:16:02.888	324.476
	51	24 Sep 2012 21:18:06.187	24 Sep 2012 21:23:00.595	294.408
	52	25 Sep 2012 08:51:54.882	25 Sep 2012 08:56:54.103	299.221
	53	25 Sep 2012 20:59:49.826	25 Sep 2012 21:03:47.815	237.988
	54	26 Sep 2012 08:33:22.107	26 Sep 2012 08:37:30.328	248.220
	55	26 Sep 2012 20:42:11.453	26 Sep 2012 20:44:03.597	112.143
	56	26 Sep 2012 22:16:41.715	26 Sep 2012 22:18:28.786	107.070
	57	27 Sep 2012 08:15:07.068	27 Sep 2012 08:17:37.063	149.995
	58	27 Sep 2012 09:51:20.086	27 Sep 2012 09:52:26.043	65.957
	59	27 Sep 2012 21:56:38.280	27 Sep 2012 22:00:45.070	246.790
	60	28 Sep 2012 09:31:05.642	28 Sep 2012 09:34:57.944	232.302
	61	28 Sep 2012 21:37:22.869	28 Sep 2012 21:42:22.906	300.036
	62	29 Sep 2012 09:11:41.527	29 Sep 2012 09:16:32.455	290.928
	63	29 Sep 2012 21:18:20.126	29 Sep 2012 21:23:46.304	326.178
	64	30 Sep 2012 08:52:32.738	30 Sep 2012 08:57:53.705	320.966
	65	30 Sep 2012 20:59:28.118	30 Sep 2012 21:04:59.869	331.751
Global Statistics				

Min Duration	7	3 Sep 2012 23:11:55.163	3 Sep 2012 23:12:12.857	17.695
Max Duration	47	22 Sep 2012 21:55:22.906	22 Sep 2012 22:00:55.051	332.144
Mean Duration				260.607
Total Duration				16939.475

Table 13. LEO Complete Chain Access report (continued)

For architecture B PowerSat's orbital altitude was set to 22,000 km with an inclination of 45 degrees. Table 14 shows the complete chain access report for a single spacecraft with these orbital elements over 30 days. Using the STK walker function the MEO PowerSat was used to build several constellation configurations with multiple planes and multiple spacecraft per plane attempting to achieve continuous coverage of the target sites. In order to provide continuous coverage of both ground sites a constellation of 9 spacecraft in a 3 plane by 3 spacecraft per plane configuration was required as shown in Figure 20.

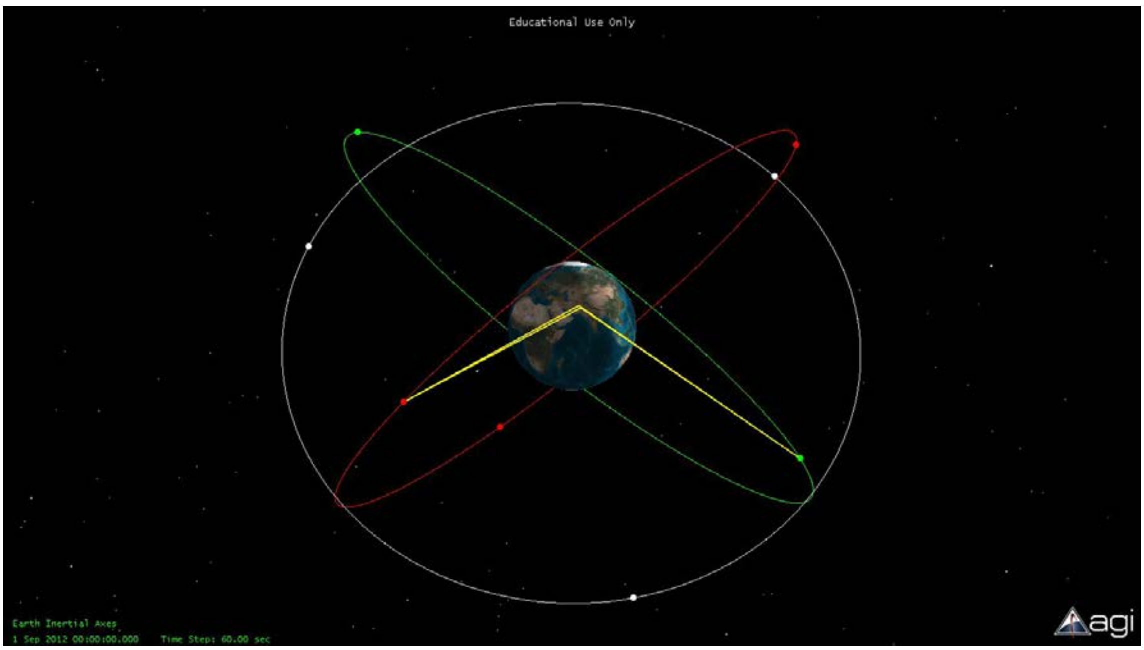

Figure 20. MEO access between Quetta and Afghan1

21 Aug 2012 14:59:23

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Chain-PowerChain: Complete Chain Access

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	1 Sep 2012 00:00:00.000	1 Sep 2012 07:10:03.410	25803.410
2	2 Sep 2012 03:31:48.064	2 Sep 2012 10:34:16.711	25348.647
3	3 Sep 2012 07:50:29.178	3 Sep 2012 12:54:26.467	18237.289
4	3 Sep 2012 17:32:47.271	3 Sep 2012 20:58:08.612	12321.341
5	4 Sep 2012 18:50:29.425	5 Sep 2012 01:01:25.227	22255.802
6	5 Sep 2012 21:43:11.905	6 Sep 2012 05:35:10.357	28318.452
7	7 Sep 2012 01:44:48.357	7 Sep 2012 09:19:00.915	27252.558
8	8 Sep 2012 06:18:36.095	8 Sep 2012 12:01:09.282	20553.187
9	8 Sep 2012 17:31:57.903	8 Sep 2012 19:07:49.025	5751.121
10	9 Sep 2012 10:33:10.213	9 Sep 2012 12:43:00.646	7790.433
11	9 Sep 2012 17:51:45.899	9 Sep 2012 23:27:51.810	20165.911
12	10 Sep 2012 20:25:18.387	11 Sep 2012 03:53:18.332	26879.946
13	12 Sep 2012 00:02:26.773	12 Sep 2012 07:59:07.161	28600.388
14	13 Sep 2012 04:43:26.243	13 Sep 2012 10:59:04.495	22538.251
15	14 Sep 2012 08:48:24.540	14 Sep 2012 12:34:24.115	13559.576
16	14 Sep 2012 17:03:11.362	14 Sep 2012 21:56:37.538	17606.177
17	15 Sep 2012 19:11:58.395	16 Sep 2012 02:08:55.427	25017.032
18	16 Sep 2012 22:28:42.867	17 Sep 2012 06:33:54.452	29111.585
19	18 Sep 2012 03:02:20.577	18 Sep 2012 09:50:41.178	24500.601
20	19 Sep 2012 07:15:03.465	19 Sep 2012 11:59:31.949	17068.484
21	19 Sep 2012 16:28:21.237	19 Sep 2012 20:24:27.526	14166.288
22	20 Sep 2012 18:03:35.778	21 Sep 2012 00:28:14.195	23078.417
23	21 Sep 2012 21:03:30.919	22 Sep 2012 05:02:08.320	28717.401
24	23 Sep 2012 01:15:49.881	23 Sep 2012 08:37:20.577	26490.696
25	24 Sep 2012 05:43:36.006	24 Sep 2012 11:10:55.858	19639.852
26	24 Sep 2012 16:12:52.888	24 Sep 2012 18:44:46.098	9113.211
27	25 Sep 2012 10:22:47.269	25 Sep 2012 11:09:52.860	2825.591
28	25 Sep 2012 17:01:31.946	25 Sep 2012 22:52:53.885	21081.938
29	26 Sep 2012 19:43:37.798	27 Sep 2012 03:22:58.259	27560.461
30	27 Sep 2012 23:30:40.937	28 Sep 2012 07:19:26.458	28125.520
31	29 Sep 2012 04:10:11.398	29 Sep 2012 10:12:11.227	21719.828
32	30 Sep 2012 08:16:02.461	30 Sep 2012 11:28:48.163	11565.702
33	30 Sep 2012 16:08:16.120	30 Sep 2012 21:21:03.303	18767.183

Global Statistics

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
Min Duration	27	25 Sep 2012 10:22:47.269	25 Sep 2012 11:09:52.860	2825.591
Max Duration	18	16 Sep 2012 22:28:42.867	17 Sep 2012 06:33:54.452	29111.585
Mean Duration				20349.463
Total Duration				671532.281

Table 14. MEO Single Spacecraft Complete Chain Access Report

3. Analysis Plan for Non-Functional Requirements

Using the information gleaned from research, this section will establish some basic rationale for how each non-functional requirement of the system was judged.

a. Reliability

The ground segment portions of Architecture A are comprised of power transforming gear and high power RF transmitting and receiving equipment. Much of this equipment exists, has few moving parts and is highly reliable. The transmitting antenna and rectenna themselves are very durable technologies. The space segment would require a pair of large deployable antennas that are also proven technologies.

The ground segment portions of Architecture B add the complexity of high power lasers in continuous operation and a photovoltaic array. Lasers operate in many existing applications to with high degrees of reliability although high power lasers do not usually operate in continuous modes. This raises some concern as to the reliability of the high powered laser. Also photovoltaic technology is simple and tends to be reliable. Similar performance might be expected of the space segment equipment.

b. Availability

In the STK model created for this analysis the constellations were sized such that the systems will both have continuous potential availability barring any interference. Both architectures would also have some impact from weather however architecture B would be more susceptible to cloud coverage that could significantly degrade the beam quality.

c. Operability

A major factor affecting the operability of architecture A relates to the huge number of spacecraft the operator would have to manage. This could be mitigated with software, but there will still be a need for large amounts of human intervention for the inevitable anomalies and orbital maneuvers in the crowded space that is LEO. Part of that management would include the analysis intensive work to prevent other spacecraft from being illuminated by the power beams. Another factor to consider for architecture A is the sheer size of the rectenna at 400 m in diameter would complicate the users operation of the system and site selection of the system. Architecture B has the advantage of a relatively small constellation of nine spacecraft. This small number of spacecraft will not be an undue burden on the operators and the physical size of the downlink receiver is only a mere 14.6 meters in diameter so would be much easier for the user to find a place for and operate.

d. Transportability

The key to assessing the transportability for architecture A is the physical size of the rectenna. In order to pick up and move this huge antenna significant amounts

of effort in disassembly and packing would likely be required as well as assembly at a new site. As for architecture B the receiving array might even be vehicle deployable, however the array itself may be fragile depending on its construction.

e. Safety

Both architectures would require significant safety systems and reasonable population standoff distances for the receiving locations. Architecture B also could be a hazard to flight aided by the use of night vision goggles. A beam of several hundred kW of infrared radiation could blind night vision systems.

4. The Analysis Plan outputs

The analysis plan described earlier is populated in Table 15 with values based on the rationale above and then weighted as to their relative importance and combined to achieve a value for performance.

Requirement	Weight	Architecture A	Raw Architecture B	Weighted A	Weighted B	Maximum
Deliver Power	3	29	29	87	87	87
Reliability	3	21	19	63	57	87
Availability	3	29	29	87	87	87
Operability	1	15	24	15	24	29
Transportability	2	9	24	18	48	58
Safety	1	20	12	20	12	29
		RF	Laser	290	315	377

Weight Values	Scale for raw input	
1--3	0--9	Barely or Does not meet requirement
	10--19	Partially meets requirement
	20--29	Meets meets to exceeds requirement

Table 15. Performance Assessment Analysis

5. Cost Analysis

Table 16 shows the calculations to come up with life cycle cost of the system. The ground segment costs were assumed to be both the same in number and near the same cost so were not considered here. The spacecraft cost was set to $350 million for the architecture A spacecraft. Since long distance wireless power transfer has been

demonstrated on a large scale using RF and not by using lasers the cost of the architecture B spacecraft was assumed to be 20% higher. Those prices and the values for the number of spacecraft arrived at in previous analysis were combined to find a subtotal for the fixed spacecraft cost. The price for output power calculated in the earlier analysis and a lifespan of 10 years was used to calculate the cost of power delivered by the system.

Calculating Cost			
		Architecture A	Architecture B
Number of Spacecraft		242	9
Spacecraft Price (Millions of dollars)		$350,000,000	$420,000,000
Fixed cost of spacecraft	cost = price * units	$84,700,000,000	$3,780,000,000
Price of delivered power ($/kW/h)		$64.77	$3.28
Power delivered by system (kW)		500	500
10 years of continuous operation to a single site (h)		87600	87600
Lifetime Power cost	cost = price*hours*kW	$2,836,926,000.00	$143,664,000.00
Total System Cost		$87,536,926,000.00	$3,923,664,000.00

Table 16. Total Cost

Now that cost has been established it can be analyzed as an independent variable against performance. Table 17 shows the cost and performance determined above with the performance normalized by dividing by the maximum number of points possible in the analysis plan. This data is then plotted in Figure 21.

Alternative	Cost ($B)	Performance	Normalized Performance
A	$87.50	290	0.77
B	$3.90	315	0.84

Table 17. Cost and Normalized Performance

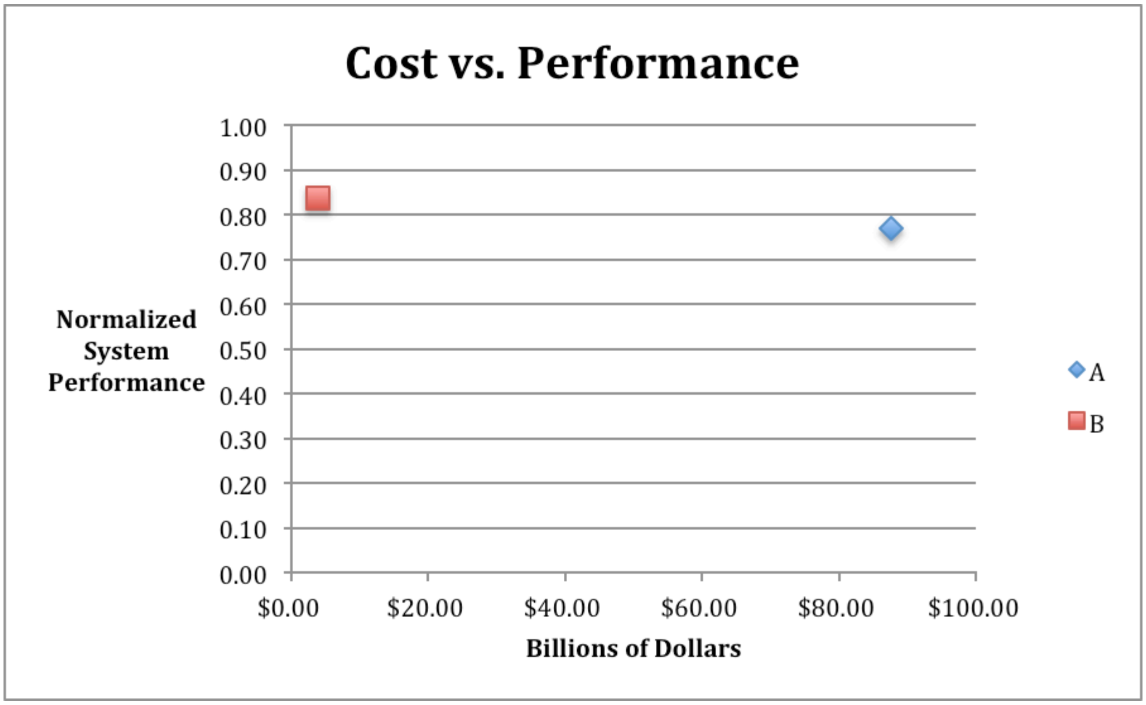

Figure 21. Cost vs. Performance.

V. CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL SUMMARY OF WORK

The question this research sought to answer is whether or not it is feasible for a space-based system using wireless power transfer technology to relay power to a remote base from a location with a commercial grid. A review was conducted of the literature concerning wireless power transfer. Much of the literature that is on the topic of space systems using wireless power transfer is from research conducted on the development systems to collect solar power and transmit it to Earth. The two wireless power transfer methods examined in this research both use electro-magnetic radiation. One method operates in the part of the spectrum known as radio using high power transmitters and the other operates in the near infrared using lasers. These two methods were integrated into architectures and modeled and analyzed to determine which one was the more feasible.

B. CONCLUSIONS

The answer to the question is that such a system is feasible. The cost that U.S. forces pay to provide logistics to remote locations is more than just in terms of dollars and gallons of fuel. That cost also comes in terms of the lives of the men and women both military and civilian that are rolling targets in hostile land. Any decision on fielding a wireless power relay system would have to weigh those costs as well.

The analysis focused on pitting one architecture and its underlying wireless power technology against another. Looking at the analysis it is clear that the system known as architecture B using lasers to transfer power is slightly less capable in meeting the non-functional requirements but is the more feasible system on a total system cost basis. This would be true even if the cost to develop the technology was to increase the cost by an order of magnitude. Architecture A using RF wireless power transfer loses far more power from end to end than does the laser method and also needs to be in a much lower orbit in order to operate at all which causes the system to require vastly more spacecraft to achieve global coverage. The laser-based relay is not without challenges however. Some of those challenges include technology development as well as weather effects and

safety concerns. Despite these challenges it is clear that if a space based wireless power transfer system is pursued that the right course of action would be to develop a system based on the laser to photovoltaic relay postulated in architecture B of this research.

The cost as an independent variable analysis does demonstrate the clear advantages of the laser-based architecture over the RF based architecture. What further analysis could accomplish would be to adjust the system capabilities especially to the RF based architecture to see if cost could be brought down. Alternately the requirements could be re-examined

An area of research that was not discussed at length in analysis is the global electrical generation availability. The detail to be gained from that piece of research is simply that anywhere on the Earth that would require the systems suggested here is not very far from a country with a decent power grid, especially in and around urban centers. There are countries that are literally islands and large distances isolate some, but if the architecture is constructed using a MEO constellation the footprint of the spacecraft would be sufficiently large to encompass some location with electrical infrastructure.

C. AREAS FOR FUTURE WORK

The goal of reducing the cost of logistics to remote bases may be better served by using airborne power relays. One of the main issues with using a space-based system is that of beam spread at orbital distances. Research into stable high altitude long dwell time aircraft could make regional wireless power transfer a reality. The power output levels of existing laser systems would need to be increased to make systems capable of transmitting the levels of power described in this research.

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